N 69 14012
NASA CR 98599

CASE FILE
COPY

REPORT NO. 2

NASA RESEARCH GRANT

NGL 22-011-024

REPORT NO. 2

NASA RESEARCH GRANT NGL 22-011-024

A STUDY OF MICROMINIATURIZED DEVICES FOR BIOASTRONAUTICAL MONITORING OR ANALYSIS

by

B. L. Cochrun

J. S. Rochefort

Electronics Research Laboratory
Northeastern University
Boston, Massachusetts

1 September 1968

The research reported here was sponsored by the National Aeronautics and Space Administration under Research Grant NGR 22-011-024 for the period from 1 September 1967 through 1 February 1968 and Research Grant NGL 22-011-024 from 1 February 1968 through 31 August 1968. This report is published for information purposes only and does not represent recommendations or conclusions of the sponsoring agency.

RESEARCH STAFF

Basil L. Cochrun, Co-principal Investigator
Associate Professor of Electrical Engineering

J. Spencer Rochefort, Co-principal Investigator
Professor of Electrical Engineering

K. Hergenrother
Research Associate

H. Mahdi
Phd. Candidate

TABLE OF CONTENTS

I. Introduction

During this report period close liaison has been maintained between the personnel of Northeastern University and those of NASA-ERC. Discussions and a free interchange of ideas have been of mutual benefit to both parties. For one example, as a result of his work on blood oximeters, done under the auspices of this grant, Mr. Bloom upon graduation joined the staff of NASA-ERC. For another, two students interested in medical electronics were employed during their school periods to do a study of electrodes. In both cases their results were obtained with only minimal expenditure of funds from the grant.

The original proposal for NASA Grant NGR 22-011-024 covered the areas of low power electrode amplifiers, solid state light sources and blood oximetry. Since the renewal of the grant on a step-funded basis, NASA Grant NGL 22-011-024, the scope of the grant has been expanded to include digital filters and active circuit synthesis using RC distributed lines. The former topic is being carried out by an undergraduate student and a master's candidate. The latter topic will be the subject of a doctoral thesis by Mr. H. Mahdi, a Phd candidate in the Electrical Engineering Department.

The two new topics are germane to the fundamental interests of the grant. Both are concerned with a significant reduction in size and an improvement in reliability for electronics systems which are matters of vital interest to both the NASA programs and the medical field in general.

II. Oximetry

At the close of the period covered by Semiannual Report No. 1, a literature search was initiated by a senior (Mr. B. H. Bloom) and resulted in a rather extensive tabulation of references. The resulting documentation is reproduced in Appendix A. Mr. Bloom then went on to write a seminar paper (84) dealing with oximetry utilizing backscattered light from the sclera of the eye. Upon graduation, Mr. Bloom joined the staff of NASA-ERC and is currently working in the same general area.

The literature survey has added additional strength to the conclusions which were reached at the time of the previous report. It appears that, from an instrument and engineering standpoint, much is to be gained from utilizing solid-state devices such as electro-luminescent diodes, photo-sensitive diodes and monolithic circuitry. Mechanical shutters, tungsten light sources and drift problems could be eliminated. Compact instruments based upon pulsed and digital processing techniques could then be employed. Accordingly, the main effort during this period has been associated with the development of electro-luminescent diodes as discussed in the next section.

Recently, however, commercial electro-luminescent materials have become available. From the standpoint of expediency it appears wise to utilize these less efficient materials to fabricate light diodes and build a prototype oximeter to demonstrate the advantage of the proposed techniques.

III. Solid State Light Sources

The need for light emitting diodes with specific spectral distributions for blood oximeters and similar projects made it necessary to have a source of (Ga_{1-x}, Al_x) As or Ga (As_{1-x}, P_x) material where x can be chosen at will. At the start of this report period such crystals were not commercially available and would not be available within the near future. Therefore, we decided to build a system to grow the required material by gas phase epitaxy. The system was specifically designed to grow (Ga_{1-x}, Al_x) since it appeared that this material would produce more efficient light sources than Ga (As_{1-x}, P_x).

Figure. 1 shows a schematic diagram of the epitaxy system which was designed and built for this project. Both the gallium and aluminum transport rely on the disproportionation of their chloride salts. It is well known that this method is successful for the transport of gallium in systems used for growing GaAs. However, the thermochemical data necessary to accurately predict the aluminum transport in such a system was not available.

During the first month of operation the system was run without any aluminum source. This was done in order to establish the operating parameters of the system while it was operating in a mode which was fairly certain of success. It was possible to grow epitaxial GaAs layers onto GaAs substrates and to change the conductivity from n to p type in a controllable manner. After the conditions for growing good GaAs layers had been established, aluminum was added to the system to attempt the growth of (Ga, Al) As and AlAs. This quickly caused etching the quartz components in much of the epitaxy system and particularly those parts which were nearest the aluminum source. Wherever possible the most severely etched components were replaced with aluminum oxide ceramic.

It was hoped at the outset that the simple addition of aluminum chloride to a system which was growing GaAs would add some aluminum to the crystal lattice and a (Ga, Al) As structure would result. This did not happen. A series of experiments were performed to study the concentration of aluminum in the epitaxial film as the growing conditions of the film were varied over a wide range of temperatures, concentrations and flow rates. Under the limits of these variations we were unable to grow any films which contained measurable aluminum. It has been concluded from this work that the growth of

(Ga, Al) As compounds and AsAs in a system using the disproportionation of aluminum chloride is not feasible.

This result is certainly due to the relative bond energies of the various chlorides of aluminum. It is presently felt that an experimental program similar to that just described where iodine is substituted for chlorine would result in aluminum transport with kinetics favorable for the growth of (Ga, Al) As. This is expected because the less energetic iodine-aluminum bond will be more sensitive to temperature changes resulting in the disproportionation reaction.

During the time the (Ga, Al) As growth experiments were in progress, the commercial availability of Ga(As_{1-x}, P_x) over a wide range in x has greatly improved. As already mentioned, this semiconductor material can also make light emitting diodes with the desired spectral output. Although the optical conversion efficiency of these diodes is not as high as it is with diodes made from (Ga, Al) As, it is expedient to make these diodes from commercially available material rather than continue the epitaxy experiments. Consequently, commercial Ga(As, P) material is being obtained with which will be made diodes for the desired wavelength.

IV. Modular Electrode Buffer Amplifier (MEBA)

A prototype MEBA has been constructed using both discrete and integrated circuitry. The circuit diagram is shown in Figure 2. The use of balanced source followers with low pinch-off FETs has the advantage of extremely high input impedance. This advantage, however, is obtained at the cost of additional gain which could be obtained by the common source configuration.

Variation of gain and output impedance with frequency is shown in Figures 3 and 4. The d-c transfer characteristics are shown in Figure 5. These curves have been obtained over a temperature range of $0^{o}C$ to $40^{o}C$ for supply voltages of $\pm$ 1.5 and $\pm$ 3.0 volts.

With the exception of open loop gain and noise requirements, it is apparent that all of the specifications listed in Semiannual Report No. 1 have been met or exceeded. Noise measurements are not yet definitive because of difficulties encountered resulting from the high input impedance. Recent acquisition of a special RFI enclosure will enable the noise measurements to be made in the near future.

It is apparent from the curves of Figures 3, 4 and 5 that the use of $\pm$ 1.5 volts severely limits the operation of the MEBA. Merely doubling V_{CC} gives a significant improvement for all characteristics. Additionally, the higher voltage would make less severe the requirements of low pinch-off voltages for the FETs.

In view of these results consideration was given to the possibility of boosting the voltage of the presently used mercury cells. A preliminary look at a voltage quadrupling circuit indicated the feasibility of obtaining higher voltages consistent with the current drain of the MEBA. The initial circuit and its characteristics are shown in Figure 6. Frequency of operation was 25 Khz. Difficulty was encountered because of the junction voltages of the solid state diodes which limits the effectiveness of the charging cycle of the circuit.

Since the inception of this idea a d-c to d-c converter has been reported using bipolar switches.[1] This circuit converted 24 volts d-c to 72 volts d-c.

Unfortunately, our low primary voltage precludes direct adaptation of this approach. Instead, it is felt that the use of FET gates which can operate with zero gate voltage will make it possible to double or perhaps triple our primary voltage with improved loading characteristics. This approach is being pursued at the present time.

A search was made for commerical operational amplifiers utilizing varactors to obtain low noise high input impedance characteristics. Only one was found, that of Analog Devices Model 1301. Tests indicated an input impedance of the order of 10^{10} ohms at room temperature. Unfortunately, the required operating voltages far exceeded the ± 1.5 volts required for our applications.

V. Electrodes for Physiological Measurements

In long term physiological monitoring, as encountered during space-flight, problems occur at the man-machine interface that are considered insignificant for short-term monitoring. These problems at the skin-electrode interface include electrode polarization, motion artifact between electrode and skin and subject discomfort.

Although much research has been conducted with electrodes, this work has been widely scattered (i.e. people in many fields such as medicine, biology, chemistry and engineering have carried on independent research) and there has been little interchange of information between these groups. In an attempt to collect this scattered information, a literature search was conducted and the results are listed in the bibliography of Appendix B.

The electrode study was carried out by two students in a two quarter project as partial credit for their degree. Their first report consisted of a search of literature and an evaluation of the information obtained therein. Report No. 2 extended the search to a survey of companies and individuals either manufacturing or doing research with electrodes. These two reports are listed at the end of the bibliography of Appendix B.

A reading of the articles listed in the bibliography indicates that the use of electrode jelly is no longer necessary. Electrode jelly is used to reduce skin-electrode impedance and to eliminate motion artifact when the subject is exercising. The high input impedance capability of today's electronic amplifiers makes possible the use of dry electrodes with their inherently larger output impedances.

The preference for dry electrodes arises from two considerations, both of which are interrelated. These are the comfort of the subject being monitored and the problem of long term monitoring. Dry electrodes do not require extensive skin preparation with its accompanying discomfort.

Dry electrodes suffer from polarization which increases the impedance and limits the lifetime of typical electrodes to about two weeks at the present time. So called non-polarizing electrodes exhibit this characteristic only at low current levels. There are the additional problems of fixing the electrode to the skin and motion artifact.

Strapping the electrode to the body is one method which is preferrable to using some form of glue which is unsatisfactory for long time monitoring. The Russians have found this method the most satisfactory for monitoring during space flights. Generally, glued-on electrodes fail due to the adhesive becoming separated from the skin.

NASA reports a new process by which electrodes may be sprayed on to the skin.[2] A nonconducting cement is mixed with powdered electrode material and sprayed onto the body. The procedure is quick and requires little skin preparation such as shaving of body hair. The sprayed-on electrode being adhesive itself eliminates the need of jelly and the problem of motion artifact. At this time no information is available on long term monitoring for this type of electrode.

Other than the sprayed-on electrode, the insulated electrode appears most promising.[3] This device which works on the basis of capacitive pick up lends itself to being strapped on the subject. No long term tests have been made, however, Dr. Richardson has indicated that this information will be passed on to us when it is available.

VI. Digital Filters

A. Introduction

Extremely accurate low-pass and band-pass filters can be constructed without employing inductors if the signal is first sampled, then processed digitally and finally passed through a simple R-C filter. This "digital filter" normally finds its application in low-frequency control systems and sampled data processing. However, since the filter itself, as well as the sampler, can be entirely constructed with micro logic circuits, this type of a device could find application in association with bio-sensors if it could be constructed compactly enough. Accordingly, a feasibility study has been in progress with this end objective in mind. As of this writing the need for a hypothetical filter has been postulated, the transfer characteristic has been expressed in the Z-transform, the values of coefficients have been determined, and a computer program has been employed to determine the sensitivity of the frequency response to parameter variation. There are no state-of-the-art limitations associated with its construction either with logic circuits or analogue processors (i.e. operational amplifiers, resistive adders, storage capacitors, etc.). Attention is currently devoted to the number, type, and size of components which would be required.

If digital filters can be constructed compactly enough, then a conventional filter could be replaced by a cascaded combination consisting of a sampler, a digital filter and a simple low-pass filter. This concept is illustrated in Figure 7. Figure 7a depicts a conventional n^{th} degree Butterworth filter while Figure 7b shows an equivalent filtering system utilizing a digital filter. To a first glance the digital system may appear bulkier, but since most components can be miniaturized, the resulting system need not be too large. In fact, in some potential applications digital transmission systems (such as PAM) may be used with the consequence that the sampler will be available and the low-pass output filter can be replaced by a gate driven at a sub-harmonic of the sampling frequency. This type of application is illustrated in Figure 7c. This system will produce an output identical to that which would be obtained if the n^{th} degree Butterworth filter of Figure 1a were followed by a sampling circuit which produced PAM pulses at the rate required by the spectral content of $y(t)$.

In order to study the feasibility of digital filtering techniques, the investigation in progress concerns the design of low-pass Butterworth filters with a cut-off frequency equal to 100 Hz utilizing data taken at 5000 samples per second (this sampling rate would be compatable with an original signal which occupied a low-pass spectrum up to 1kHz). A fifth-order and a third-order filter have been considered. In each case the investigation has been divided into two stages: the effect of parameter variation, and the effect of component size. The first stage has been ideally suited to undergraduate and masters level student participation since it has essentially involved utilizing the computer to calculate amplitude response upon incremented parameter variation. The second stage is in progress at present and is more dependent upon circuit know-how and the like for its successful completion.

B. Fifth-Order Butterworth Equivalents

The Z-transform of the transfer characteristic of a 5^{th} order Butterworth filter utilizing 5000 samples/second and realizing a 3 db point at 100 Hz is

$$H(Z) = \frac{Y(Z)}{X(Z)} = K_n \frac{Z^5 + 5Z^4 + 10Z^3 + 10Z^2 + 5Z + 1}{Z^5 + C_4Z^4 + C_3Z^3 + C_2Z^2 + C_1Z + C_0} \qquad (1)$$

where $C_0 = -0.6656525$ $\quad C_1 = 3.598902$ $\quad C_2 = -7.794918$

$C_3 = 8.455115$ $\quad C_4 = -4.593421$

and K_n is a normalization constant. The frequency response can be obtained by replacing Z by exp(jwT), where T is the interval between successive samples. The resulting spectrum is comb-like since it repeats at multiples of the sampling rate (1/T). A plot of spectral magnitude versus frequency for the first 1000 Hz is shown in Figure 8. If each coefficient is increased by +1% of its nominal value while the other coefficients are held at their nominal values, the other curves shown in Figure 8 result. This filter could be constructed with amplifiers, adders and delay units as indicated in Figure 9.

On the other hand, it is possible to factor equation (1) into the form below.

$$H(Z) = K_n \frac{Z+1}{Z+b_1} \cdot \frac{Z^2+2Z+1}{Z^2+b_2Z+b_3} \cdot \frac{Z^2+2Z+1}{Z^2+b_4Z+b_5} \quad (2)$$

where $b_1 = -0.88161859$ $b_2 = -1.80155740$ $b_3 = 0.81587612$.

$b_4 = -1.91024514$ $b_5 = 0.92542798$

Figure 10 shows a method of realizing this configuration while Figure 11 illustrates the effect of a similar +1% change in coefficient size. Here it is apparent that change in b_1, b_3 and b_5 have less effect than similar variations of any of the C's in equation (1). However, the effect of variations in b_2 and b_4 are far from acceptable. If allowed variation is reduced to +1/4%, then the curves of Figure 12 result. Since, once more, it appears to be the quadratic terms which must be controlled more carefully than the others, it was decided to narrow the study down to a third order Butterworth where but one quadratic term would be presented.

C. Third-Order Butterworth Equivalents

The Z-transform of the 3rd order Butterworth filter is given by

$$H(Z) = \frac{Y(Z)}{X(Z)} = K_n \cdot \frac{Z^3+3Z^2+3Z+1}{Z^3+C_2Z^2+C_1Z+C_0} \quad (3)$$

where $C_2 = -2.74883581$ $C_1 = 2.52823122$ $C_0 = -0.77763856$

If this equation is reduced to factors, then there results

$$H(Z) = K_n \frac{Z+1}{Z+b_1} \cdot \frac{Z^2+2Z+1}{Z^2+b_2Z+b_3} \quad (4)$$

where $b_3 = 0.88205780$ $b_2 = -1.86721722$ $b_1 = -0.88161859$

The response for equations (3) and (4) when the coefficients are each varied by +1% is shown in Figures 13 and 14 respectively. Once more it can be seen that the factored form gives better performance although the response is most sensitive to changes in b_2. Figure 15 shows an analogue method of synthesizing equation (4)

A fair amount of data has been taken in which each coefficient was varied by smaller increments. The net result appears to be that variations up to ± 0.1% are tolerable. A set of worst combinations are shown in curves of Figure 16. This tolerance limit is not a severe one since in analogue synthesis 0.5% resistors can be used to realize weighting coefficients of the order of those required (say 0.88) to within a percent (say 0.12).

When digital synthesis is contemplated then closer accuracy can be achieved. Curve I of Figure 17 shows the result when each coefficient is approximated with rational fractions. Curve II of Figure 17 results when each coefficient is approximated to within 1 part in 128. This latter approximation allows binary synthesis since each coefficient can be represented by an 8-digit binary number. The input samples could be quantized and converted into binary numbers, shifted for delay and multiplied by the binary coefficients in the usual way in which binary computer computations are carried out.

At present, as indicated earlier, the second stage of the study is in effect. Consideration is being given to component size, weight, etc., required for analogue and binary synthesis when coefficients tolerances must be held to within ± 0.1%.

VII. Active Circuit Synthesis Using Uniform and Exponential RC Distributed Lines

Mr. Hooshang Mahdi, a Phd candidate, joined the staff in May of this year. His search for a suitable doctoral thesis topic concerned with active network synthesis involved a series of seminars in the area culminating in a thesis proposal which in essence is an extension of Kerwin's[4] work involving the use of RC distributed networks.

Kerwin demonstrated the feasibility of obtaining active filters using RC distributed lines whose characteristics were superior to lumped element lines with the additional attraction of a significant reduction in size. Since reduction in size is of prime interest for all aspects of this grant, Mr. Mahdi's doctoral thesis is directly applicable to the present program.

Mr. Mahdi, in his preliminary investigation, has used analytical expressions for the admittance matrix of the distributed line for both the uniform ($\overline{\text{URC}}$) and the exponential tapered ($\overline{\text{ERC}}$) lines. This approach in conjuction with root loci techniques has allowed an evaluation of the pole zero configurations possible with distributed lines, which, in the case of the $\overline{\text{URC}}$, gives good agreement with the results of Kerwin. (The $\overline{\text{ERC}}$ was not investigated by Kerwin).

The basic circuit under investigation is shown in Figure 18. The indefinite admittance matrix of the distributed line can be expressed as

$$[YDI] = \begin{bmatrix} y_{11} & y_{12} & -(y_{11}+y_{12}) \\ y_{21} & y_{22} & -(y_{21}+y_{22}) \\ -(y_{11}+y_{21}) & -(y_{12}+y_{22}) & y_{11}+y_{12}+y_{21}+y_{22} \end{bmatrix} \tag{5}$$

The overall circuit admittance matrix becomes

$$[Y] = \begin{bmatrix} y_{11} & -(y_{11}+y_{12})+y_{12}/K \\ y_{21} & -(y_{21}+y_{22})+y_{22}/K \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \tag{6}$$

The voltage gain V_3/V_1 becomes

$$\frac{V_3}{V_1} = \frac{K}{\frac{-y_{22}}{y_{21}} + K\left(1 + \frac{y_{22}}{y_{21}}\right)} \tag{7}$$

For the case of the $\overline{URC}$ the admittance matrix becomes

$$\left[YD\right] = \frac{1}{Z_0} \begin{bmatrix} \frac{\cosh\theta}{\sinh\theta} & \frac{-1}{\sinh\theta} \\ \frac{-1}{\sinh\theta} & \frac{\cosh\theta}{\sinh\theta} \end{bmatrix} \tag{8}$$

where $\theta = d(sr_0c_0)^{1/2}$, $Z_0 = (r_0/sc_0)^{1/2}$ and $s = jw$, with r_0, c_0 and d being characteristics of the distributed line.
The voltage gain becomes

$$\frac{V_3}{V_1} = \frac{K}{\cosh\theta + K(1 - \cosh\theta)} = \frac{K}{F_1(s) + KF_2(s)} \tag{9}$$

The location of the poles and zeros and the effect of K upon their location can now be found by routine application of root loci techniques.

The $\overline{ERC}$ is shown in Figure 19. The admittance matrix for this structure can be expressed as

$$\left[YD\right] = \frac{\theta}{R} \begin{bmatrix} \frac{\cosh\theta}{\sinh\theta} \; \frac{-\alpha d}{2\theta} & \frac{-e^{-\alpha d/2}}{\sinh\theta} \\ \frac{-e^{-\alpha d/2}}{\sinh\theta} & \left(\frac{\cosh\theta}{\sinh\theta} + \frac{\alpha d}{2\theta}\right) e^{-\alpha d} \end{bmatrix} \tag{10}$$

where $\theta = \left[\left(\frac{\alpha^2}{4} - r_0C_0s\right) d^2\right]^{1/2}$ and $R = r_0d$. (Note that for $\alpha = 0$ this structure reverts to the $\overline{URC}$.)

The voltage gain V_3/V_1 becomes

$$\frac{V_3}{V_1} = \frac{K}{(\cosh\theta+\frac{\alpha d}{2\theta}\sinh\theta)e^{-\alpha d/2} + K[1-(\cosh\theta+\frac{\alpha d}{2\theta}\sinh\theta)e^{-\alpha d/2}]} \quad (11)$$

$$= \frac{K}{F_1(s) + kF_2(s)} \quad (12)$$

A combination of root locus and graphical techniques yields the approximate locations of the poles as

$$S_n \simeq \frac{-(2n+1)^2\pi^2}{4r_0C_0}\left[1 - \frac{2\alpha d}{(2n+1)^2\pi^2 + 2\alpha d}\right] - \frac{(\alpha d)^2}{4r_0C_0} \quad (13)$$

When $\alpha = 0$

$$S_n \simeq -\frac{(2n+1)^2\pi^2}{4r_0C_0} \quad (14)$$

which is the solution for the pole locations for the $\overline{\text{URC}}$ structure.

With the poles for the $\overline{\text{ERC}}$ dependent upon αd we see that there is an additional degree of freedom in relocating the poles and thereby facilitating the realization of a given pole zero configuration. Another interesting feature of the $\overline{\text{ERC}}$ is that for large values of αd, subject to fabrication limitations, the first few poles are grouped close to $-(\alpha d)^2/4r_0C_0$ which would not be possible for any lumped element circuit.

Computer programs were written to aid in the study of the magnitude and phase response of the circuit of Figure 18. The first program was concerned with the $\overline{\text{URC}}$ response and its relation to a function having a pair of complex conjugate poles having a magnitude given by

$$\left|T(s)\right| = \frac{\alpha^2 + \beta^2}{(s+\alpha)^2 + \beta^2}$$

The $\overline{\text{URC}}$ magnitude and phase response was obtained for various line time constants T, (r_0C_0), and operational amplifier gain K. Magnitude matching of $|T(s)|$ and that of the $\overline{URC}$ was obtained at two frequencies for those values of K for which the response went through a maximum. Table I gives the results of matching the responses at 0.345 and 2.0 rad/sec for K=0.7 and r_0C_0=15 seconds which gives α=-0.489 and β=0.589.

The maximum magnitude discrepancy is about 5.7% and occurs at 0.90 rad/sec. Phase discrepancies exist at all frequencies and increases from about 3^o at 0.1 rad/sec to about 100^o at 2.6 rad/sec.

A second program was written to study the magnitude and phase characteristics of the $\overline{ERC}$ for various tapering parameters αd and operational amplifier gain K. For each αd the maximally flat response was determined by searching the computer results. For a given αd such response occurs for a specific value of K. Proper selection of T ensures ω_{3db}=1.0 rad/sec for MFM response. Figure 20 is a plot of the required values of K and T required to obtain the MFM response for αd in the range $-6 \leq \alpha d \leq 14$.

Figure 20 indicates that positive tapering requires less gain than negative tapering. This implies that the requirements of the operational amplifier for the $\overline{ERC}$ will not be as stringent as those for the $\overline{URC}$. Positive tapering, however, requires a larger T which would be a disadvantage in terms of size.

Figures 21 and 22 compare the magnitude and phase of a second order Butterworth with those of the $\overline{ERC}$ active network. For large values of αd an increase in the discrepancies for magnitude and phase is obtained. This suggests that negative tapering could be used to obtain a match with respect to magnitude. This is the case for αd=-4.50. The required value of K is 0.955. Unfortunately, phase discrepancies exist at all frequencies reaching a value of about 60^o at 2.6 rad/sec. However, the phase response does match the phase response of the fourth order Thompson within -5^o up to twice ω_{3db}.

It should be noted in Figure 21 that when αd=0, giving the results for a $\overline{URC}$ with K=0.672, the response is better than the second order Butterworth in the sense that it is flatter in the pass-band and has a sharper roll off beyond ω_{3db}. The phase and magnitude response matches that of a fourth order Thompson low-pass filter. Further study has shown that a second order Thompson magnitude response can be obtained by the proper selection of T and K. The corresponding phase response matches that of a third order Thompson up to twice ω_{3db}.

In considering the $\overline{\mathrm{ERC}}$ for use as a Thompson filter it was found that it was possible to achieve an exact second order Thompson magnitude response with improved linearity for the phase response. Both magnitude and phase characteristics for the third order Thompson filter could be approximated with $\alpha d=-8$, $K=.996$ and $T=5.46$. With $\alpha d=6$, $K=0.29$ and $T=23.1$ an MFM response better than the second order Butterworth magnitude response can be achieved. The corresponding phase response matches that of the fifth order Thompson to within 7% at twice ω_{3db}. These preliminary results indicate the possibility of obtaining improved magnitude and phase response simultaneously without the compromises given by the Transition-Butterworth-Thompson (TBT) filters for circuits using lumped parameter circuits.

VIII. Projections

Work on a prototype oximeter will continue utilizing solid state light sources and digital techniques. EL diodes will be fabricated from commercially available material. The preliminary approach will be to demonstrate the superiority of this procedure over the classic use of mechanical chopping, bulky detectors and light sources. With this point definitely established consideration will be given to the problem of packaging and miniaturization.

Work in the MEBA will continue in two directions. One will be a refinement of the present model using hybrid circuit techniques taking advantage of the facilities of the integrated circuits laboratory here at Northeastern which will be functioning shortly. A second tack will be increased attention given to a more efficient d-c to d-c converter which will ease the limitations imposed by the use of mercury cells.

The investigation of digital filters will be pursued in two stages. The first stage will involve a prototype filter utilizing discrete available components. The second stage, based upon the experience of the first, will involve miniaturization using integrated techniques which are currently available.

The investigation of active circuits using distributed lines will be continued by Mr. Mahdi while he waits for his proposal to be accepted by the Electrical Engineering faculty. At this point acceptance is a mere technicality. Consequently, there will be no interruption of his work in this area.

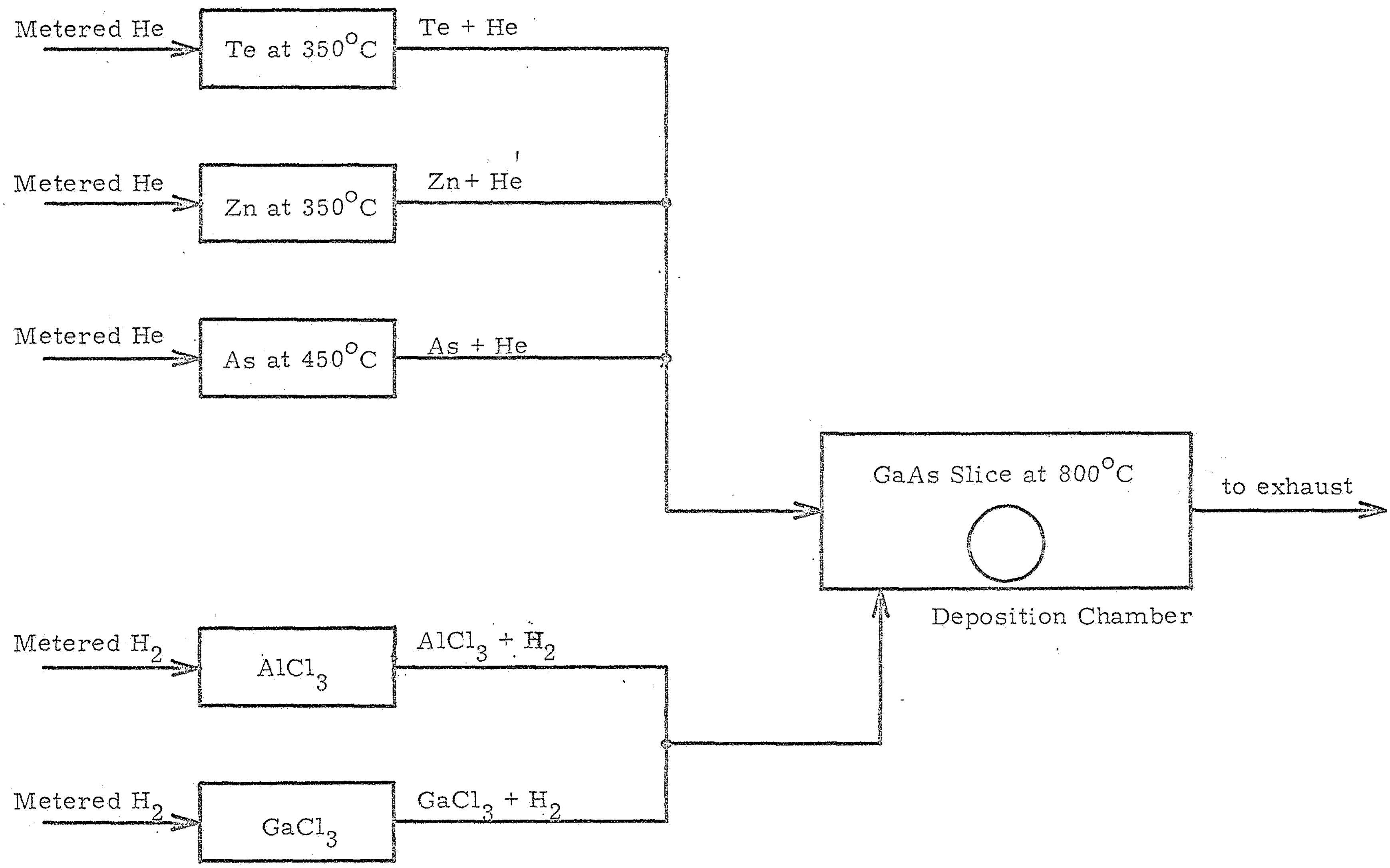

Figure 1. Block Diagram of Mixed Crystal Growing System

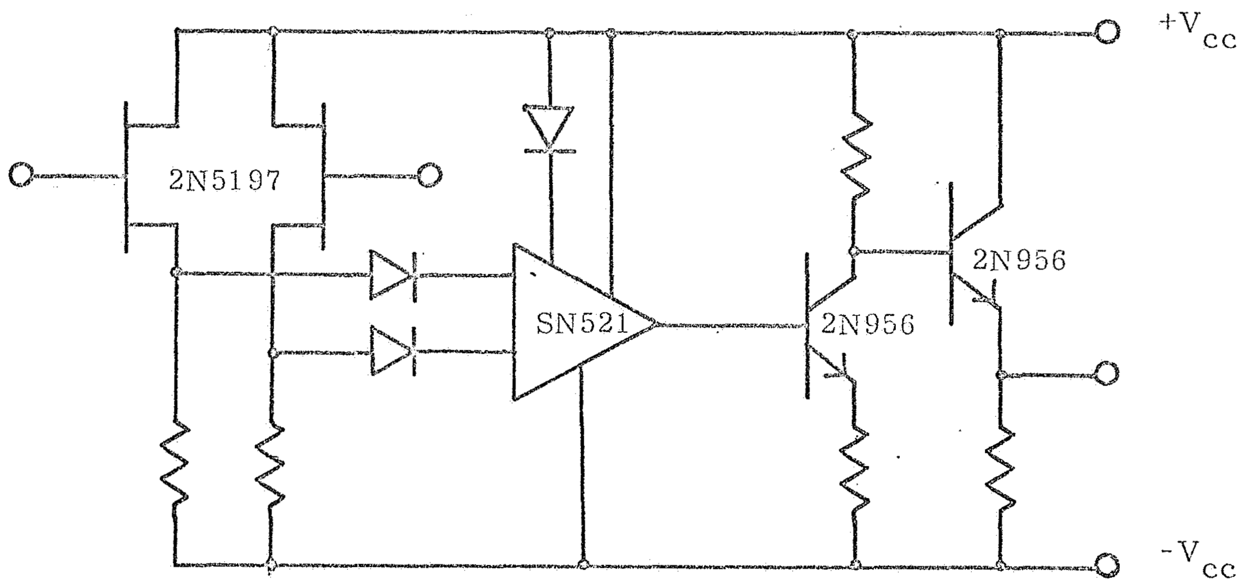

Figure 2. MEBA Circuit

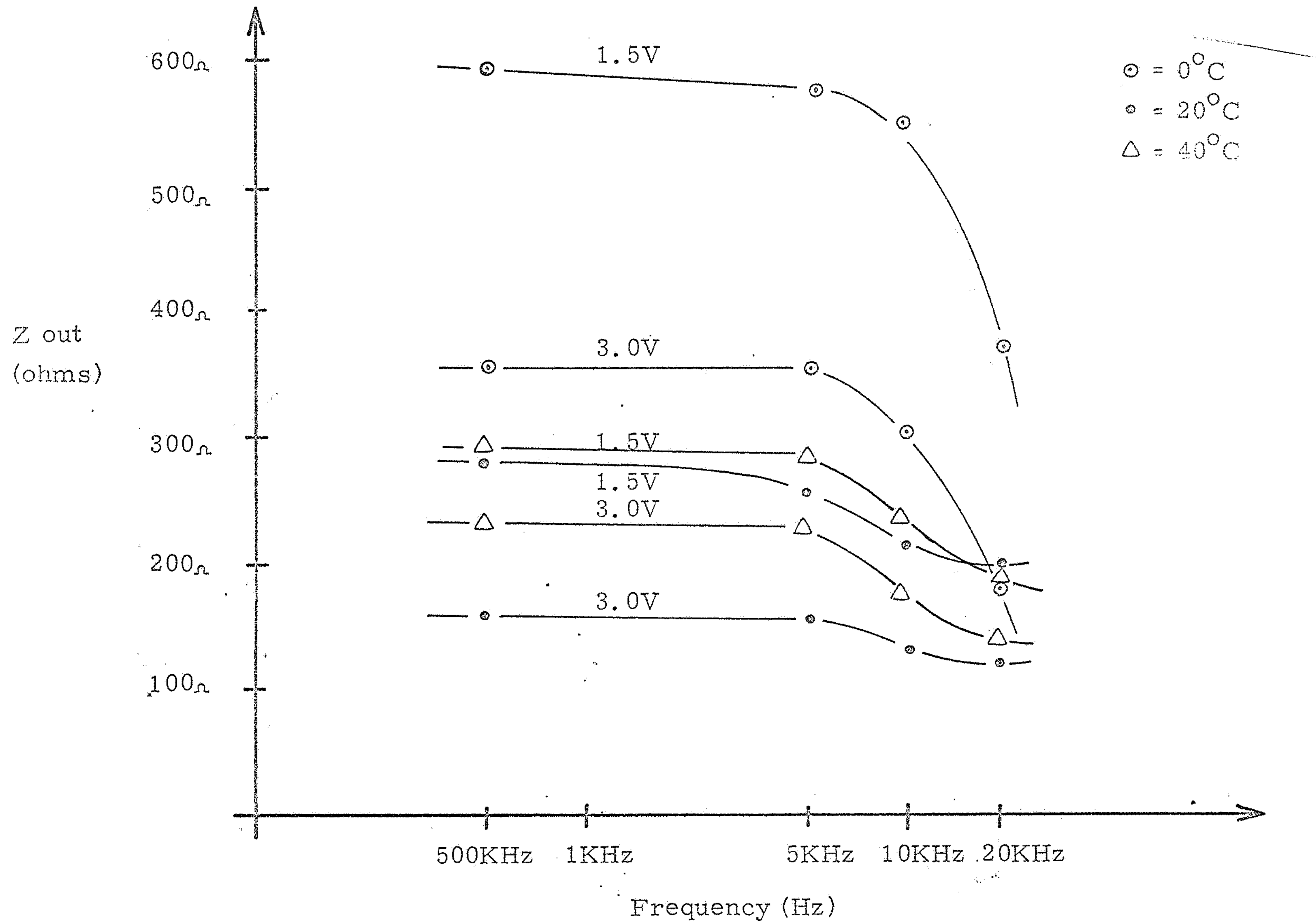

Figure 3. Z out vs. Frequency

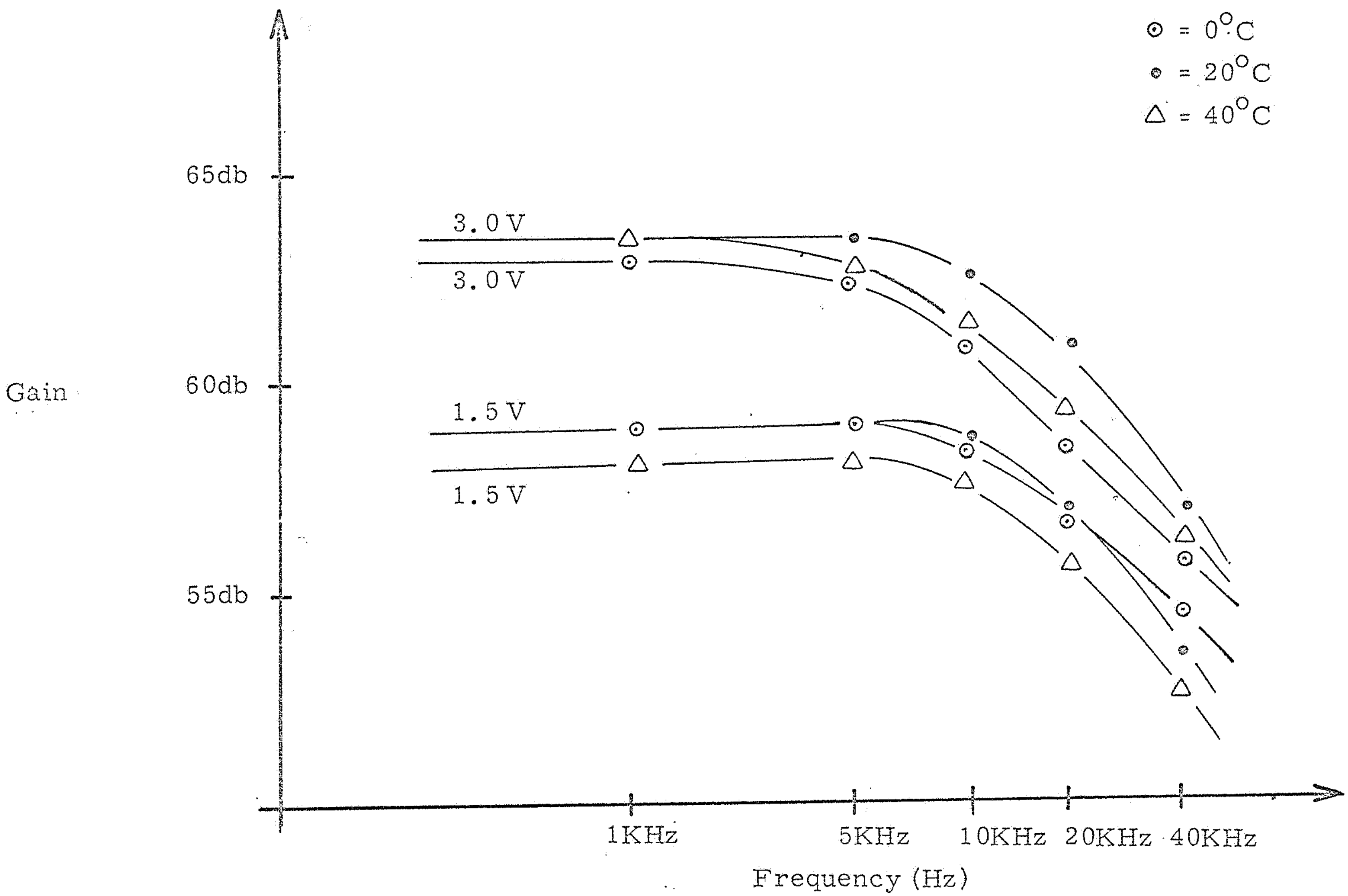

Figure 4. Gain vs. Frequency.

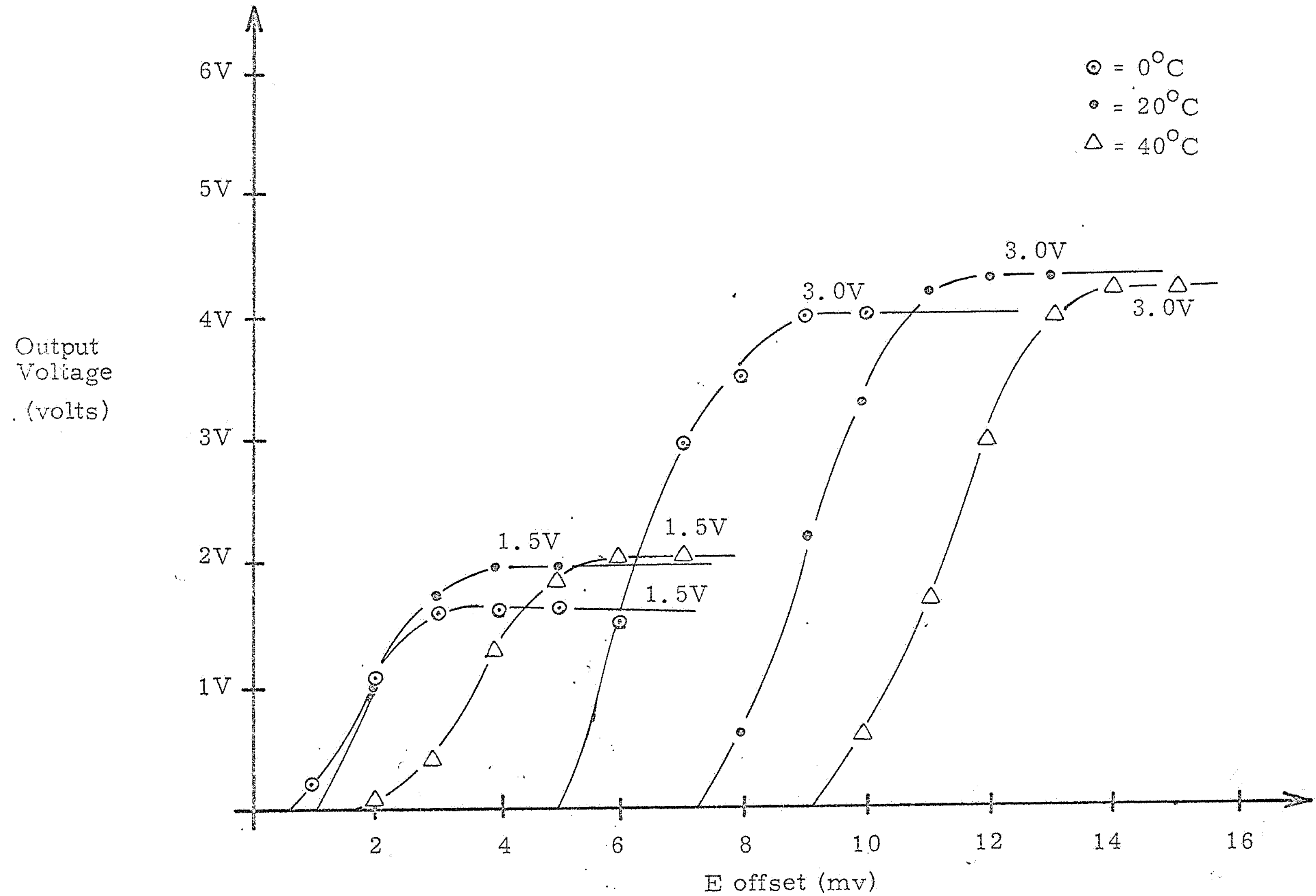

Figure 5. DC Transfer Function

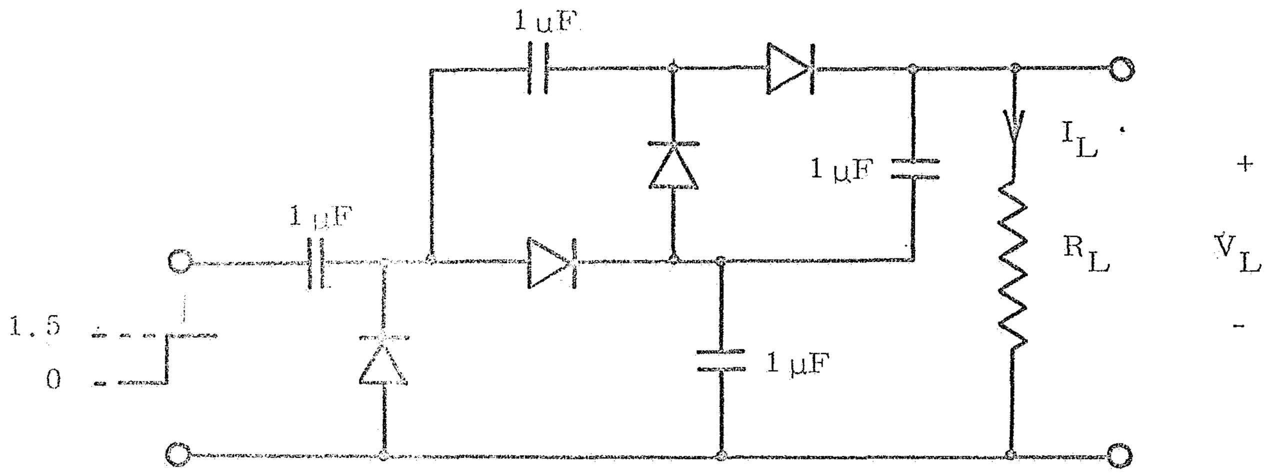

Figure 6a

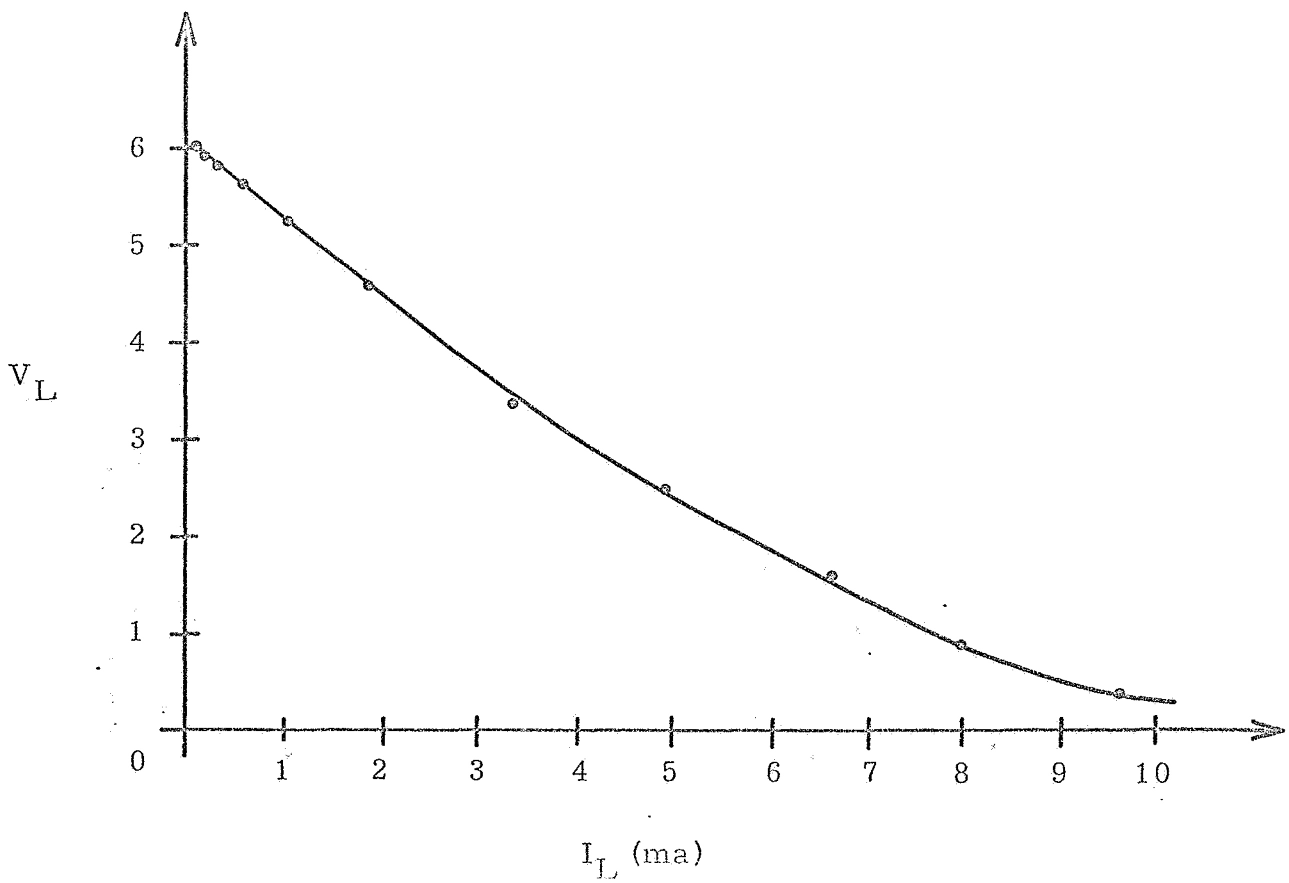

Figure 6b

Figure 6. Voltage quadrupler (a) circuit (b) load characteristics

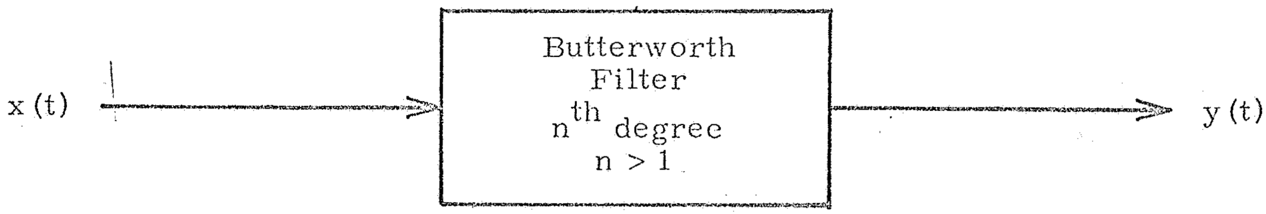

Figure 7a. Conventional Filter

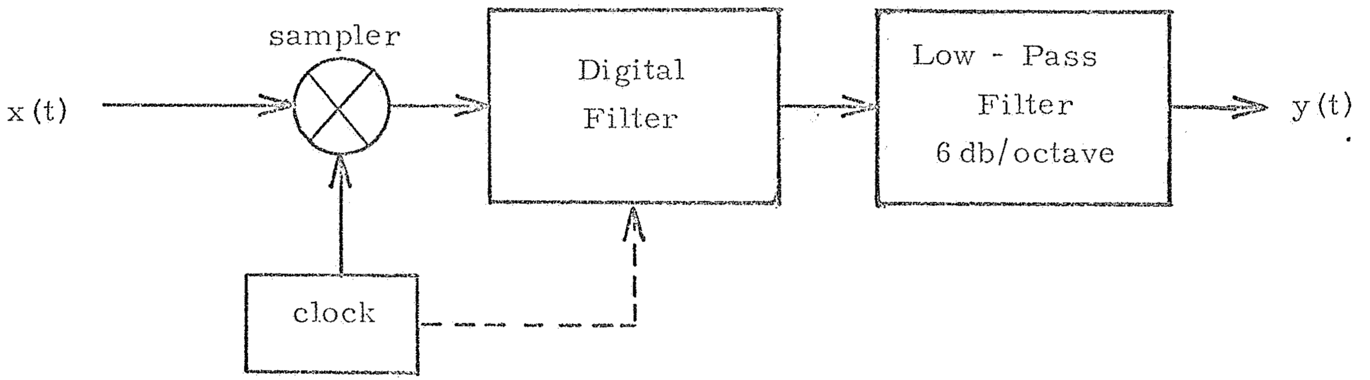

Figure 7b. Equivalent Digital Filtering System

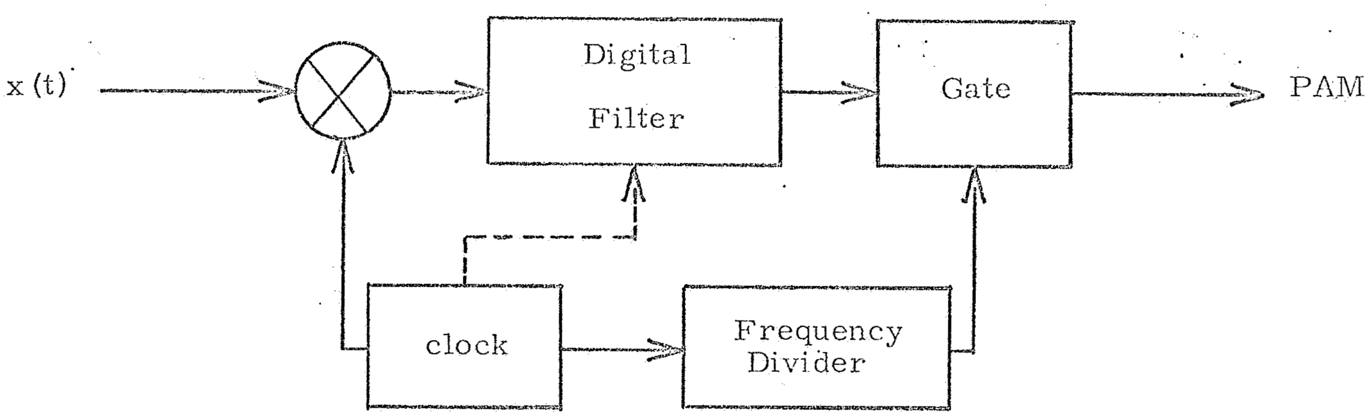

Figure 7c. Pre-filtered PAM

Figure 7. Filter concepts (a) Conventional filter (b) Equivalent digital filter (c) Pre-filtered PAM.

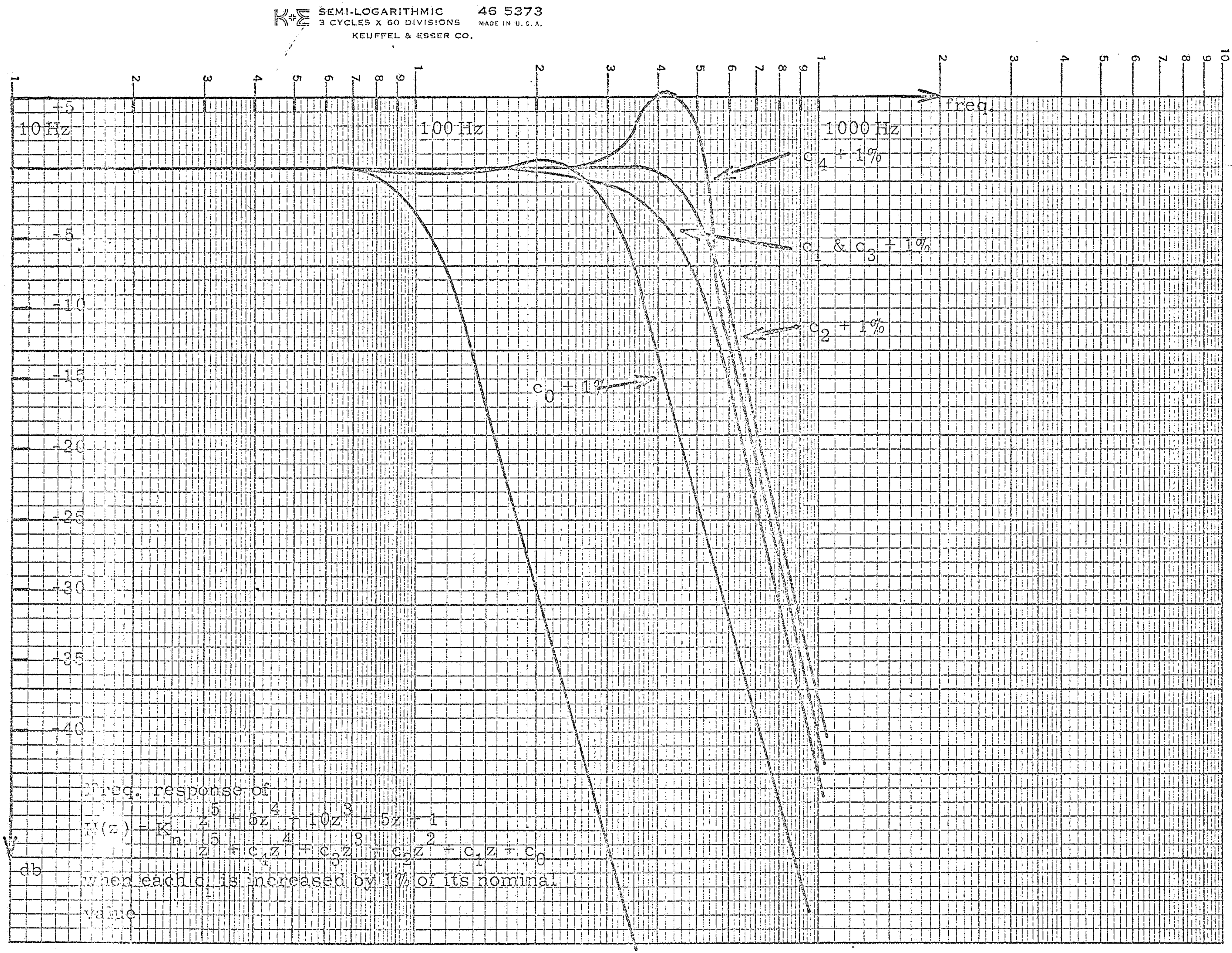

Figure 8. Fifth Order Digital Butterworth

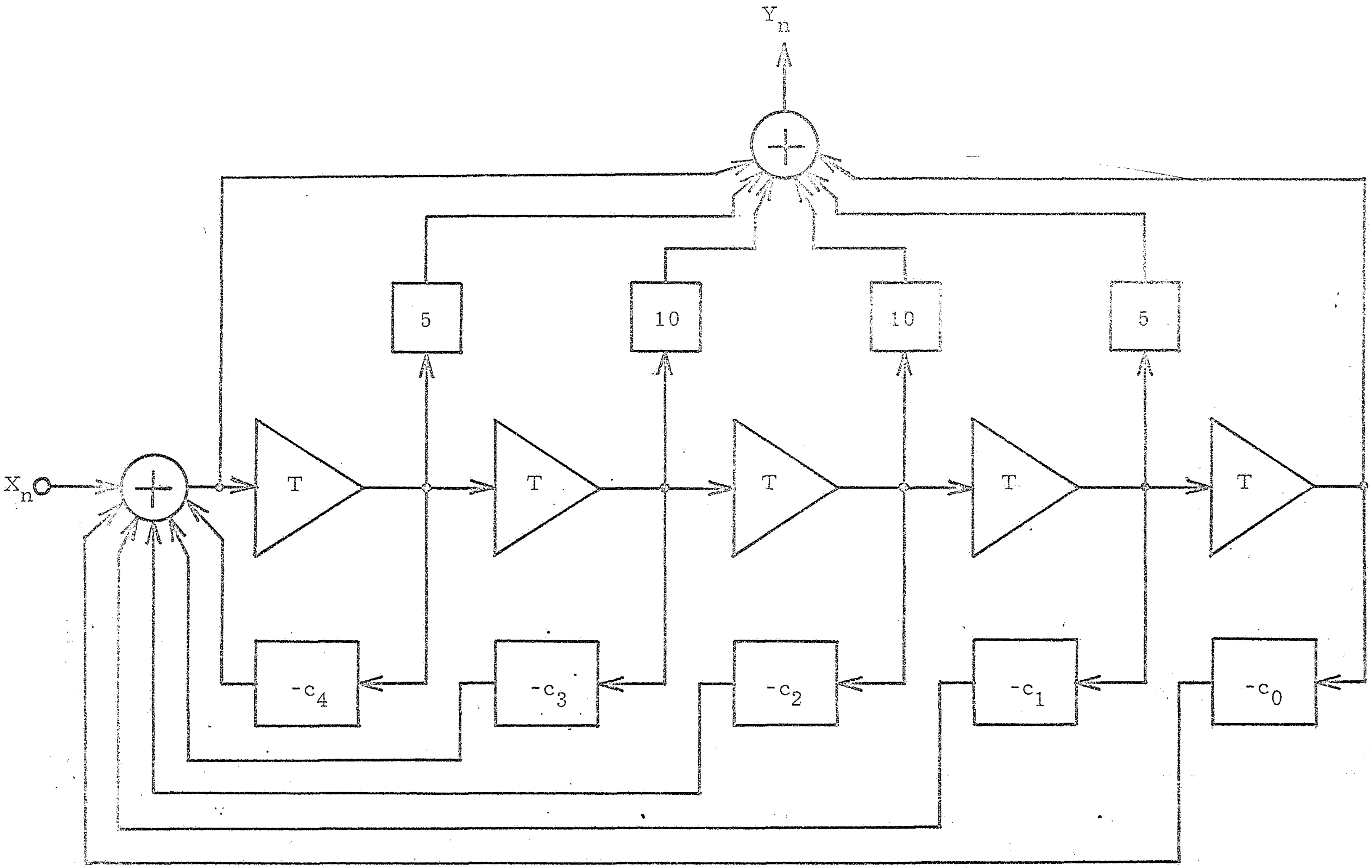

Figure 9. Implementation of Equation 1

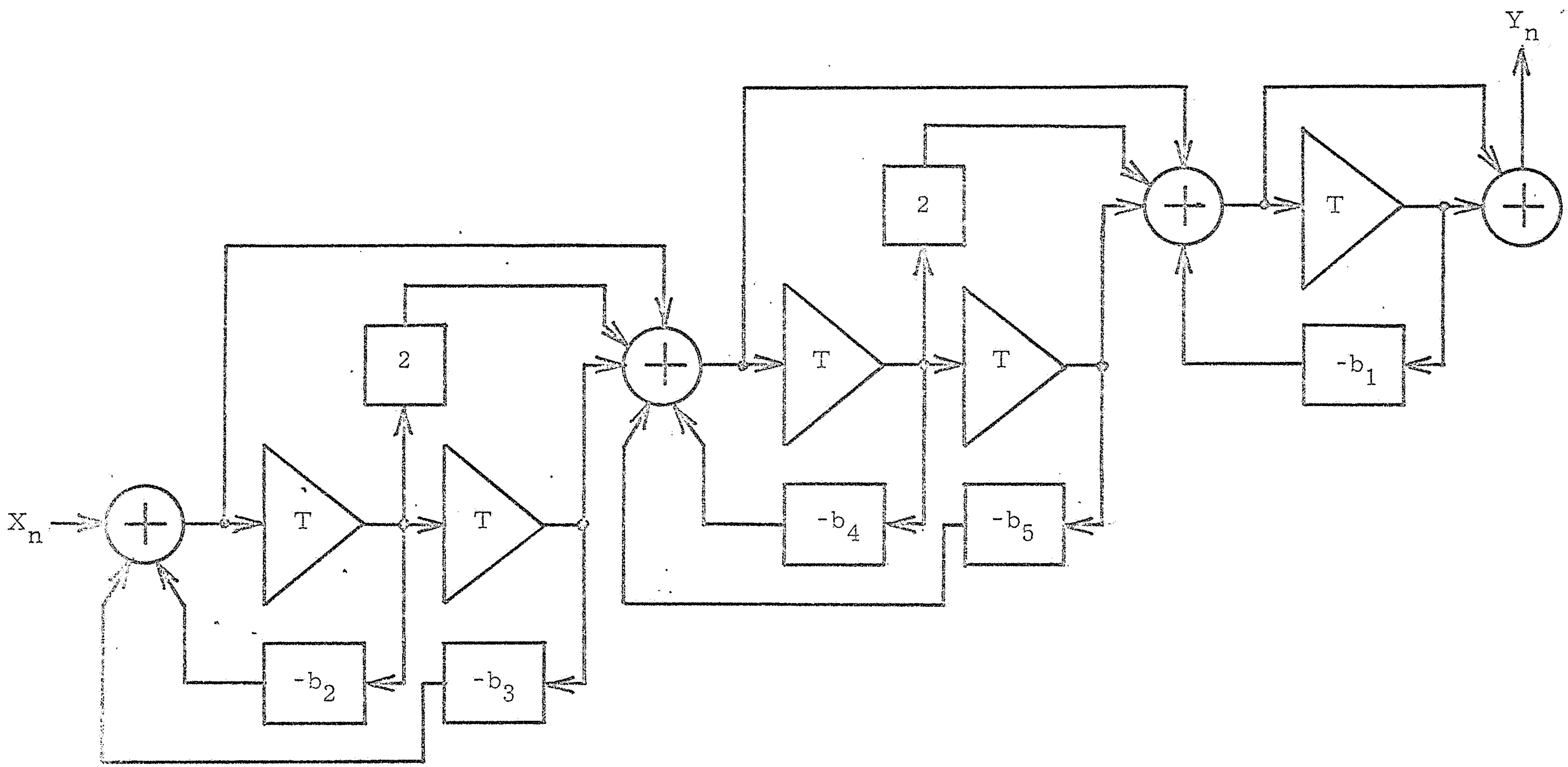

Figure 10. Implementation of Equation 2

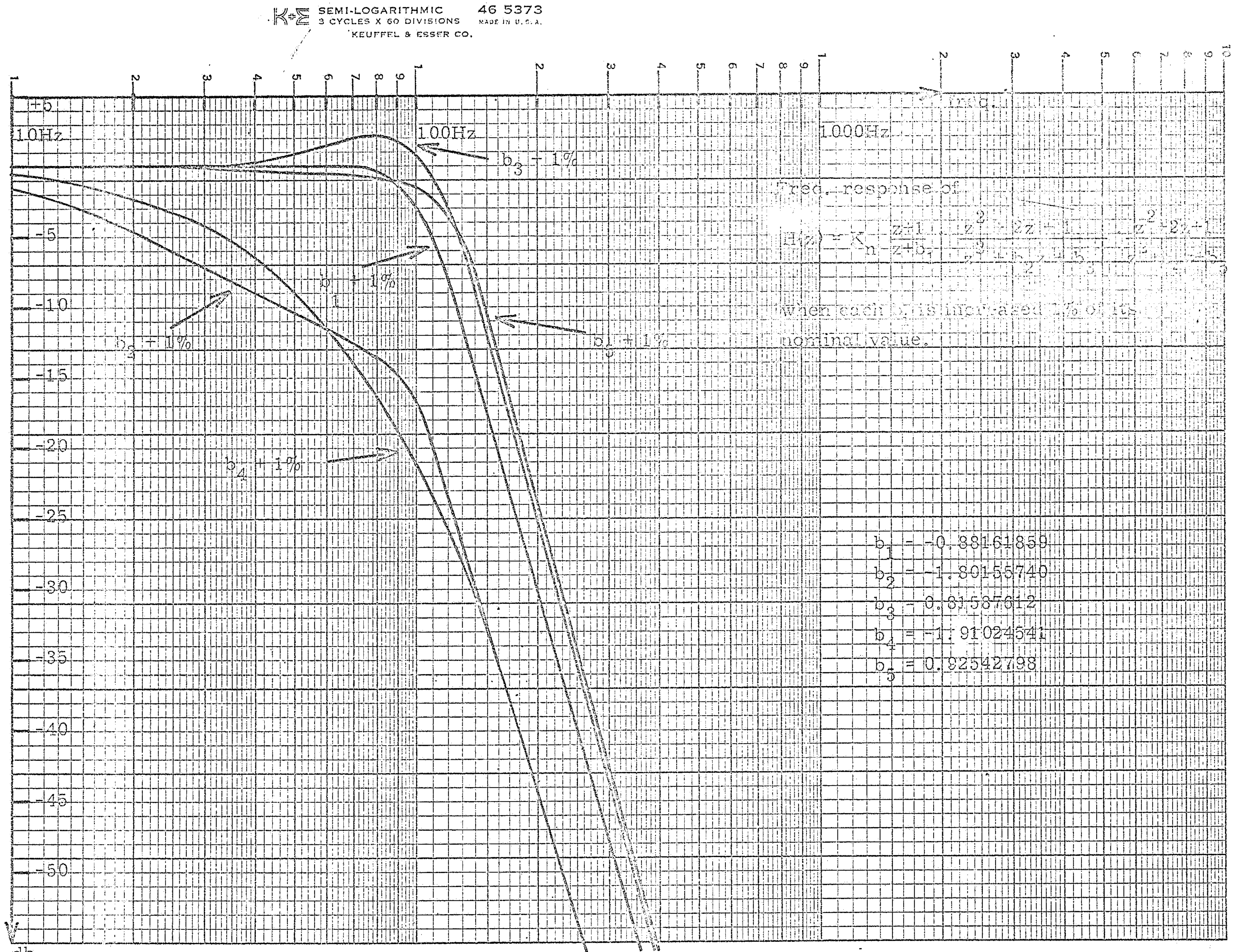

Figure 11. 1% Digital 1-2-2 Cascade

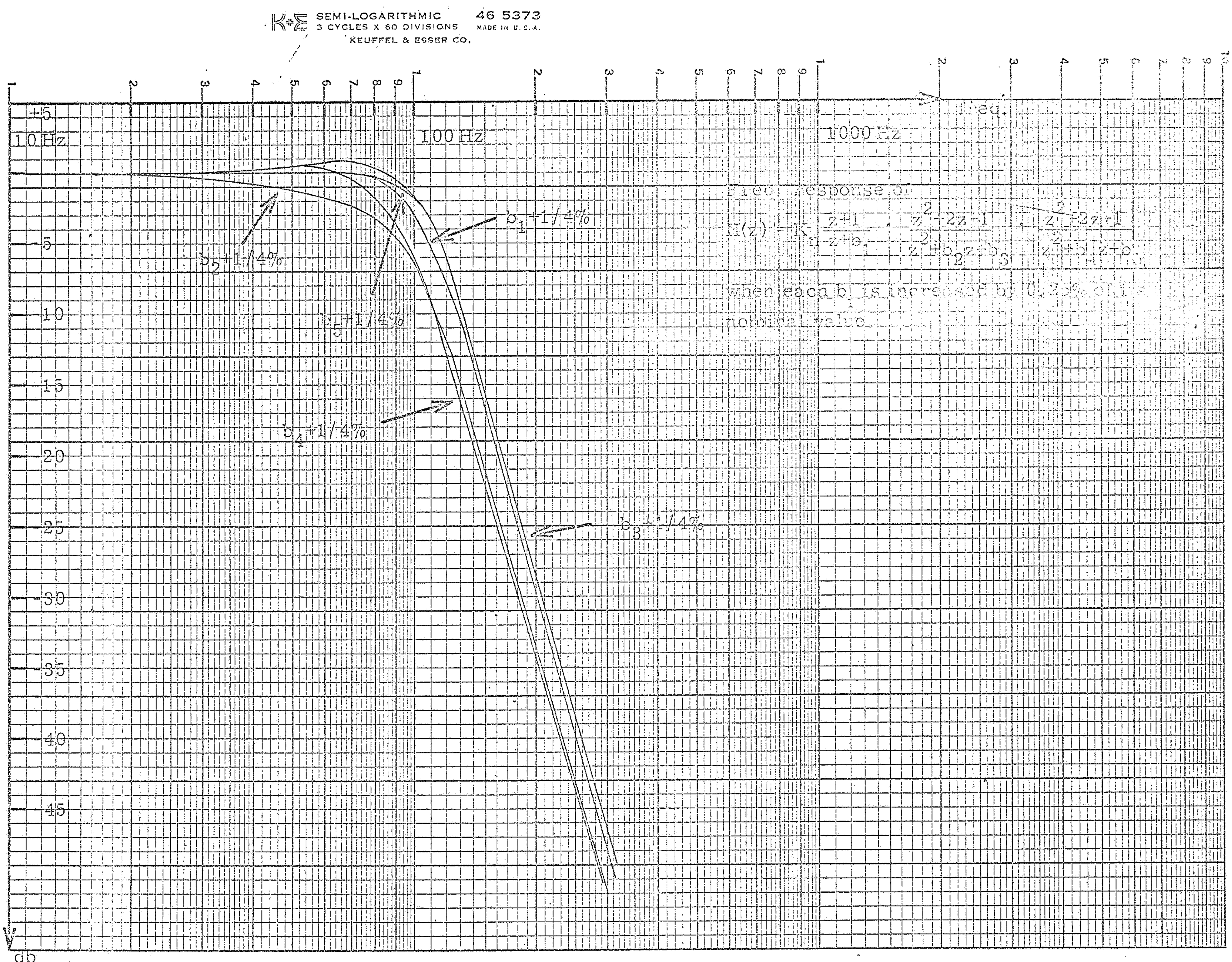

Figure 12. 1/4% Digital 1-2-2 Cascade

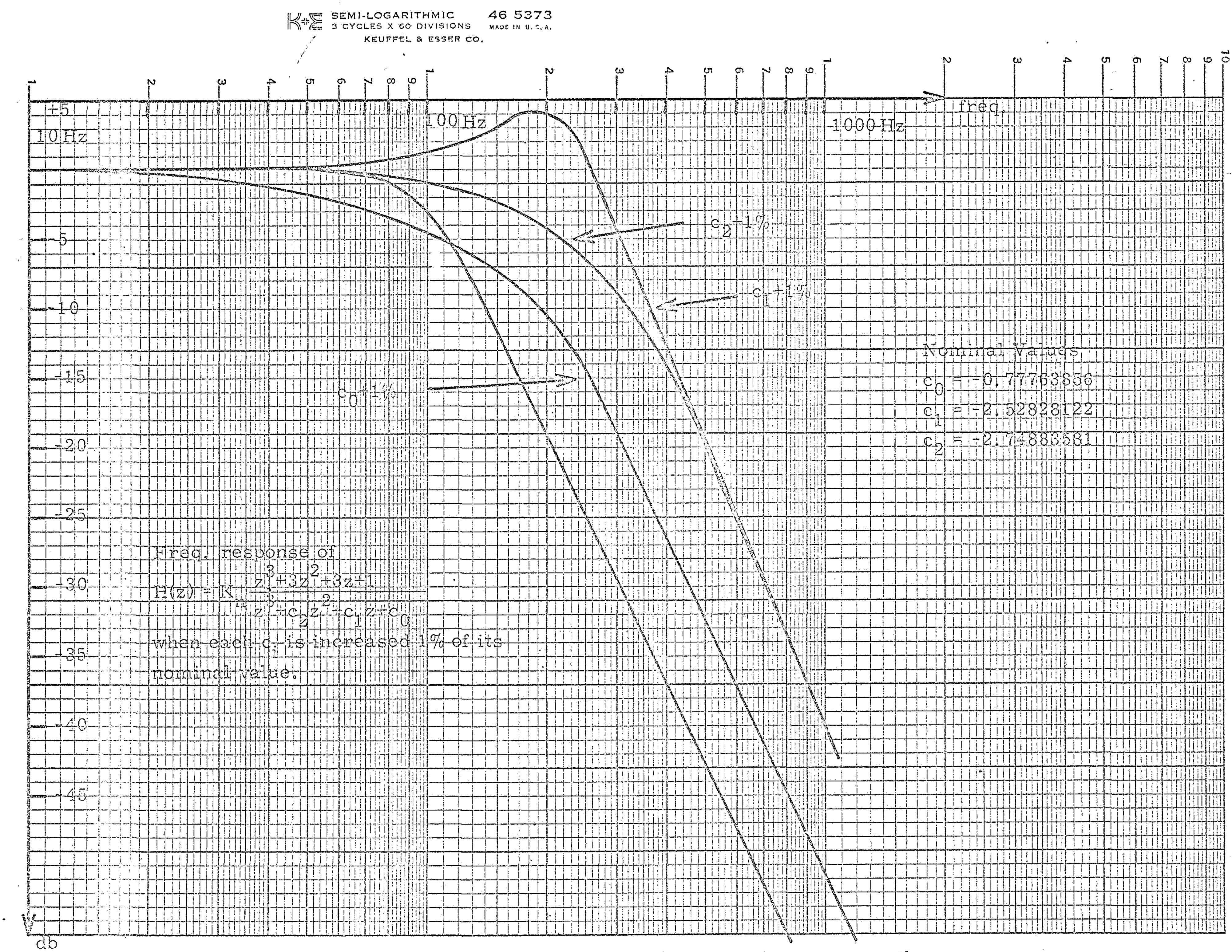

Figure 13. 1% Third Order Digital Butterworth

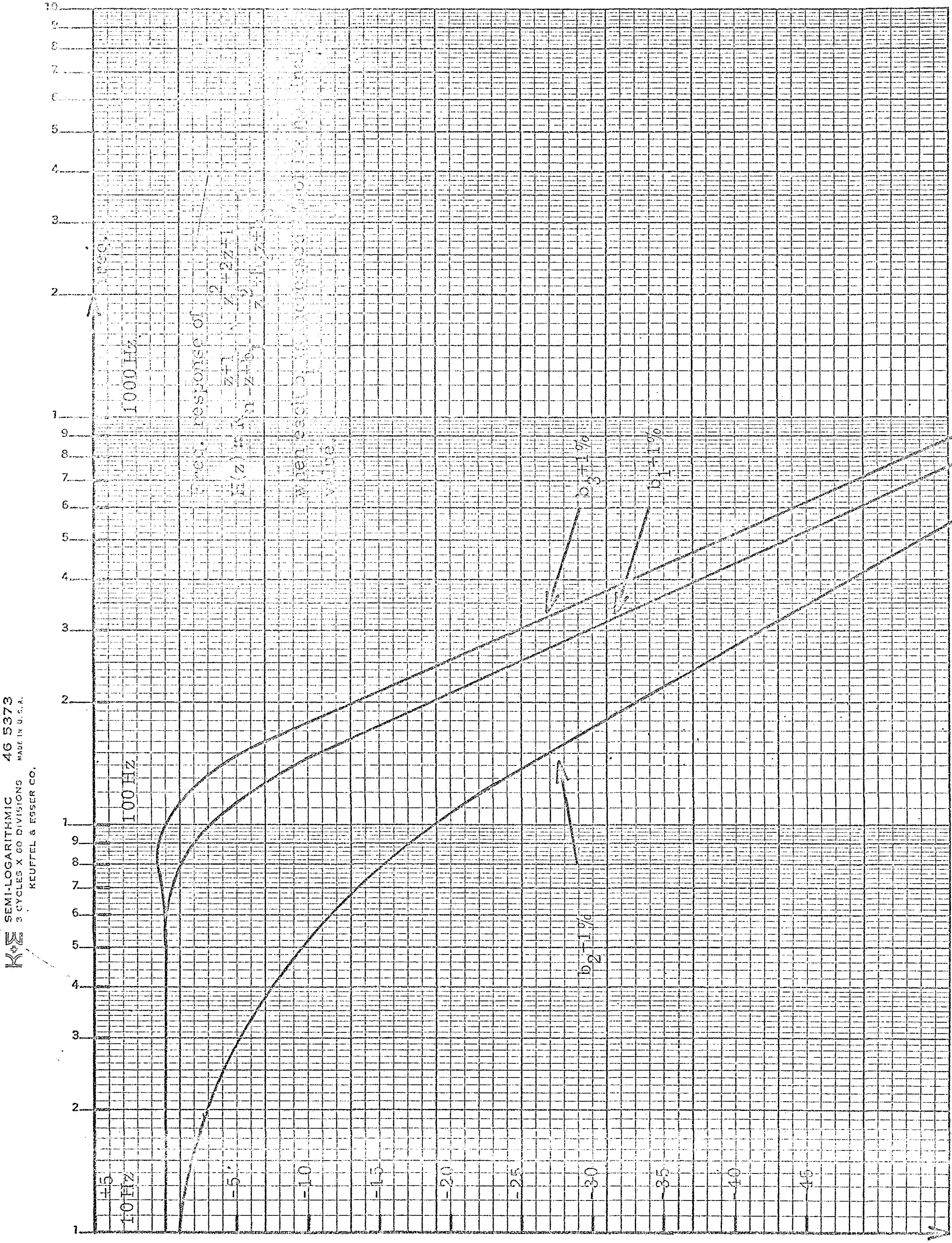

Figure 14. 1% Digital 1-2 Cascade

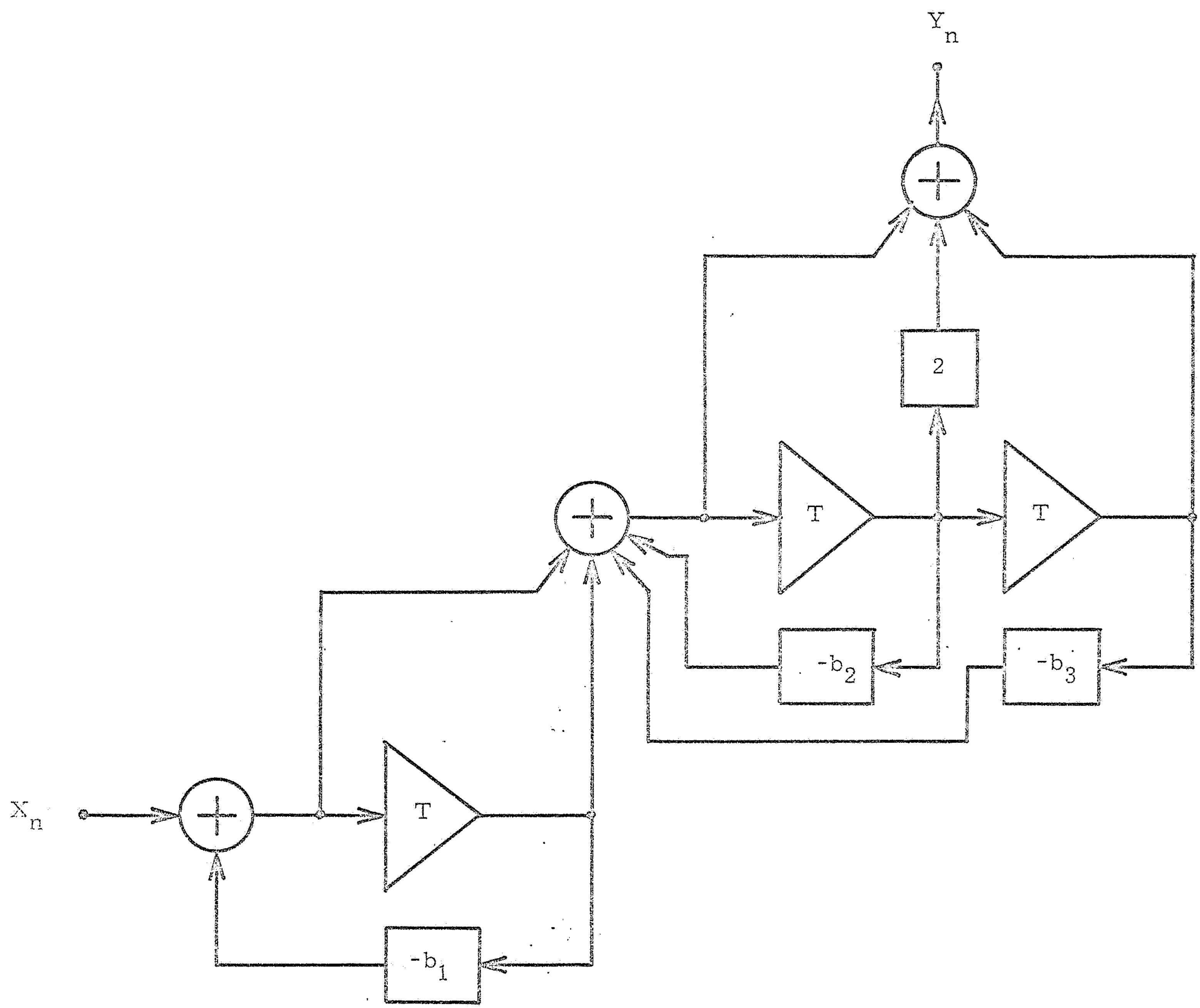

Figure 15. Implementation of Equation 4

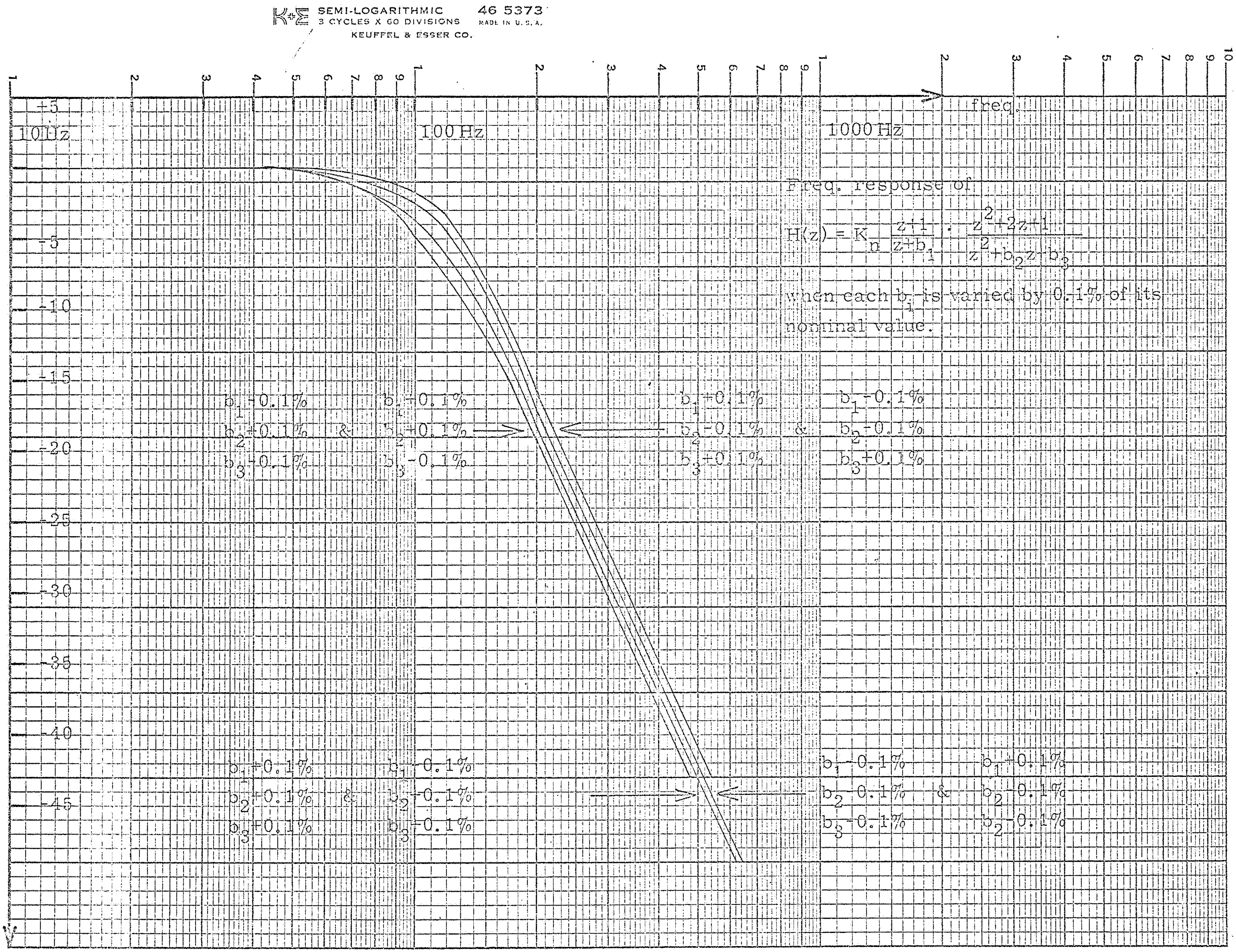

Figure 16. .1% Digital 1-2 Cascade

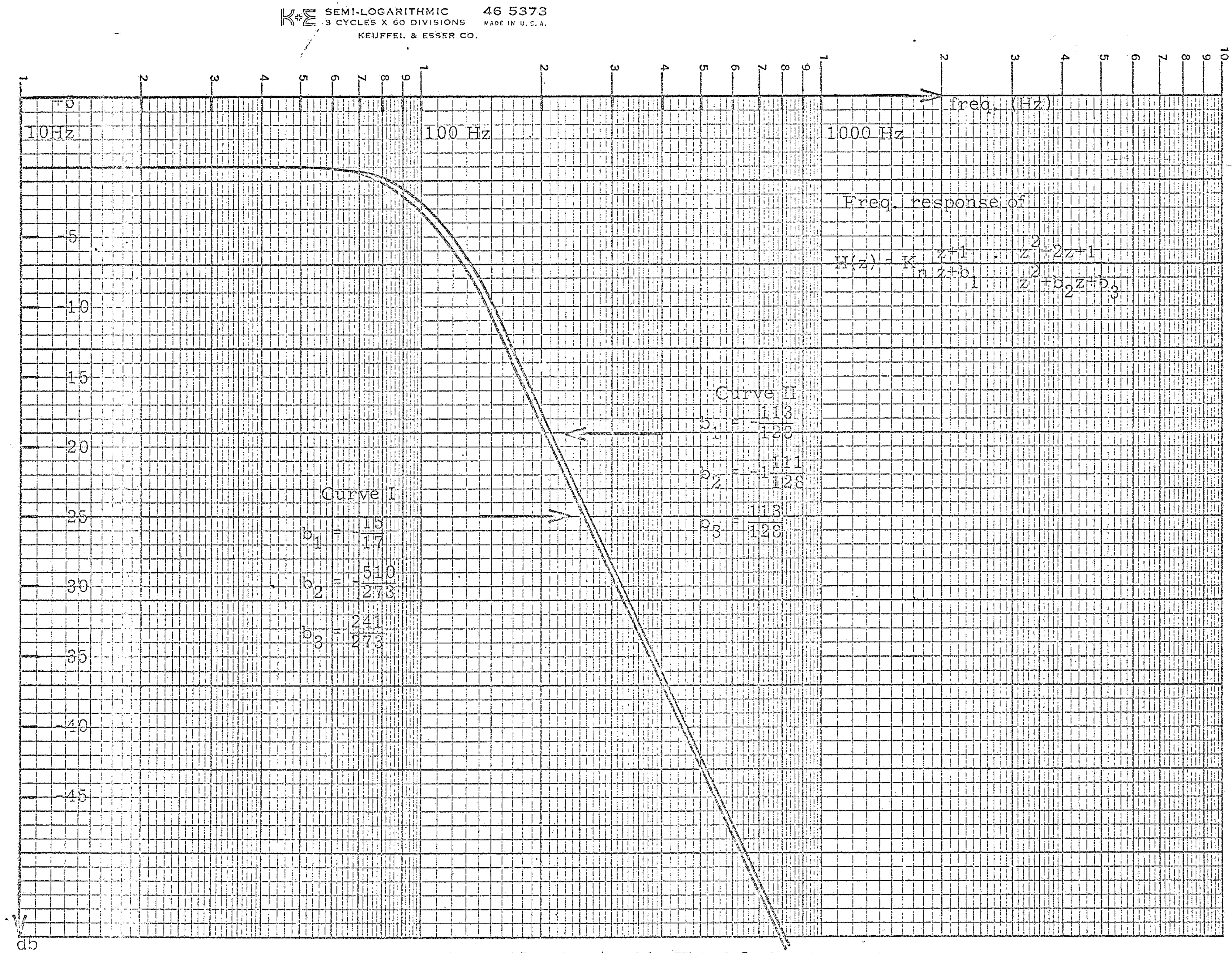

Figure 17. Acceptable Third Order Approximations

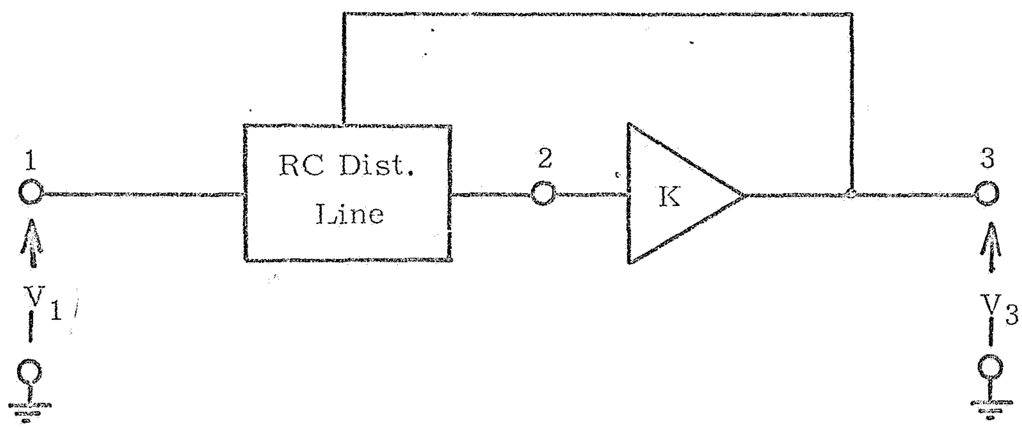

Figure 18. Basic active circuit utilizing an RC distributed line and an operational amplifier.

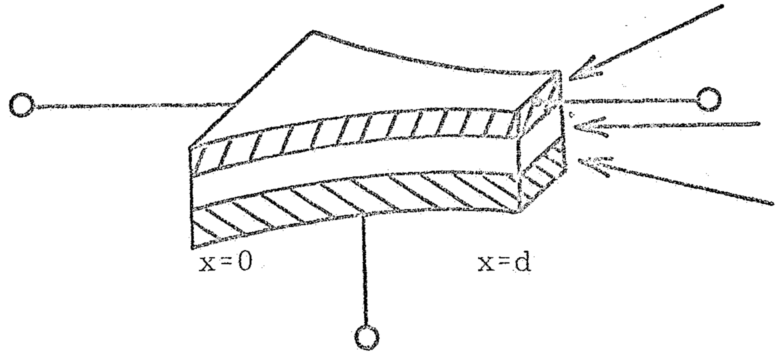

Figure 19. An exponentially tapered thin-film network, having resistance per unit length of $r_{(x)} = r_0 e^{-\alpha d}$ and capacitance per unit length of $c_{(x)} = c_0 e^{\alpha d}$.

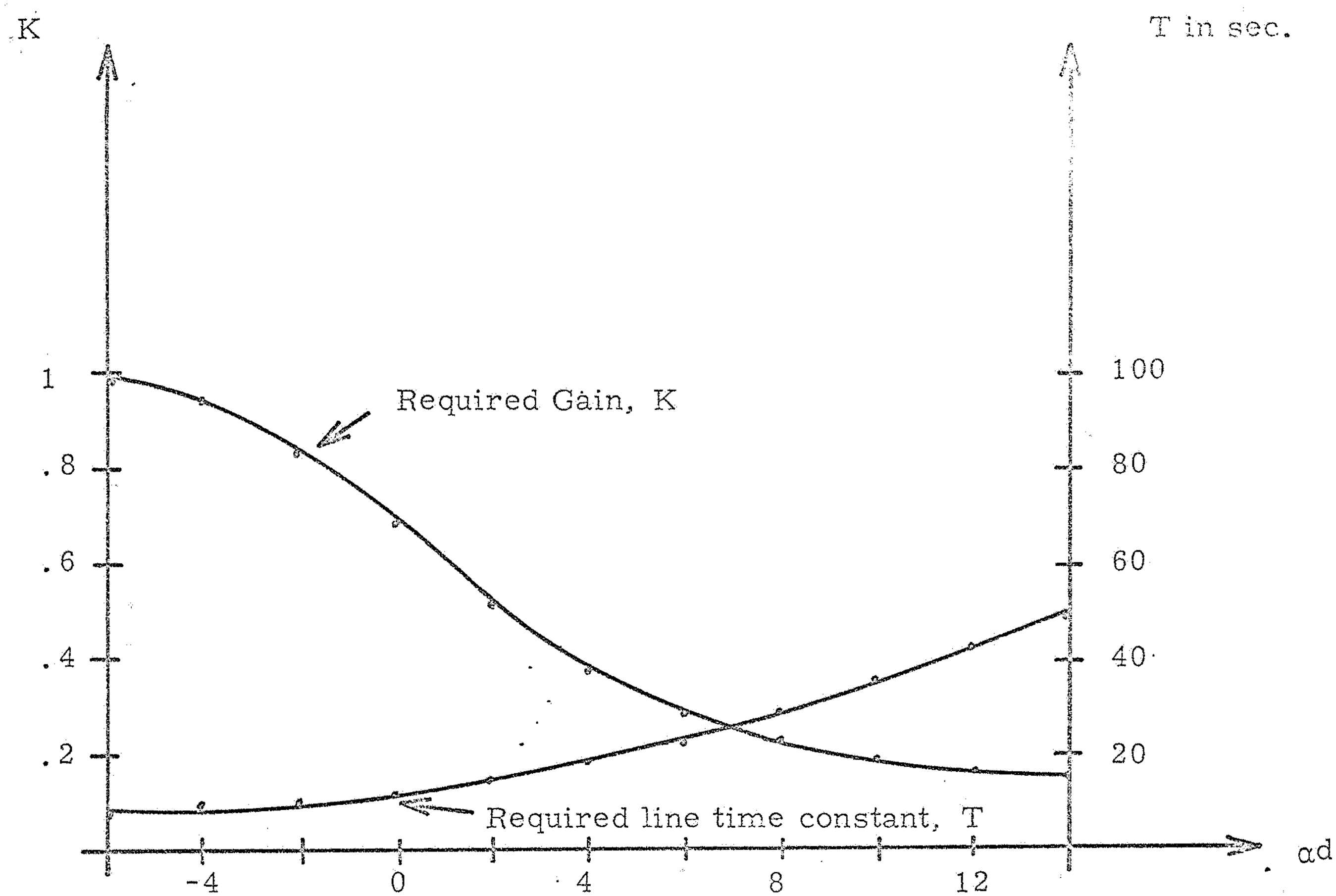

Figure 20. Required T and K for $\overline{ERC}$ AN to give MFM Response Having $\omega_{3db} = 1$ R. P. S.

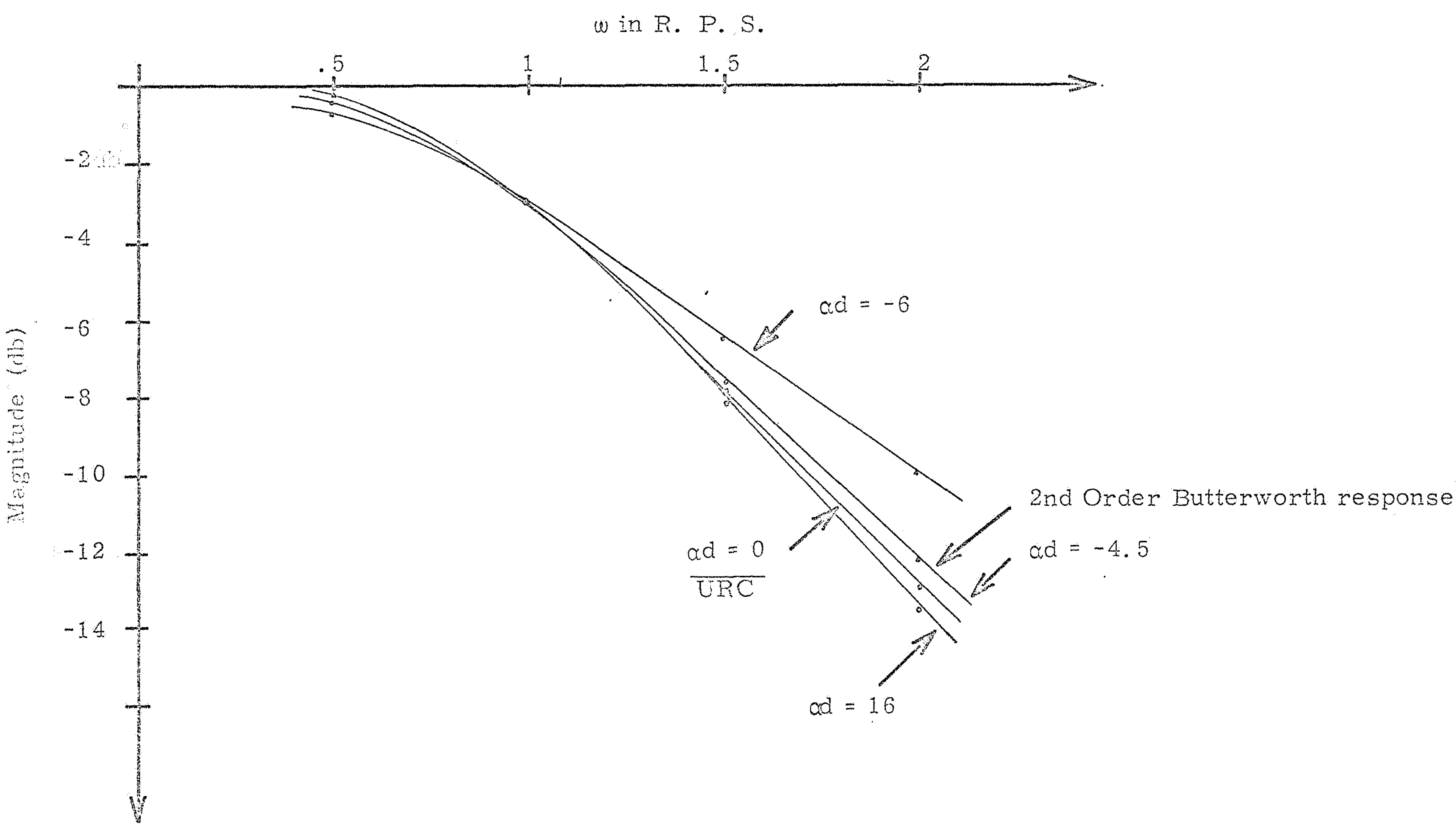

Figure 21. Magnitude Response for Various αd

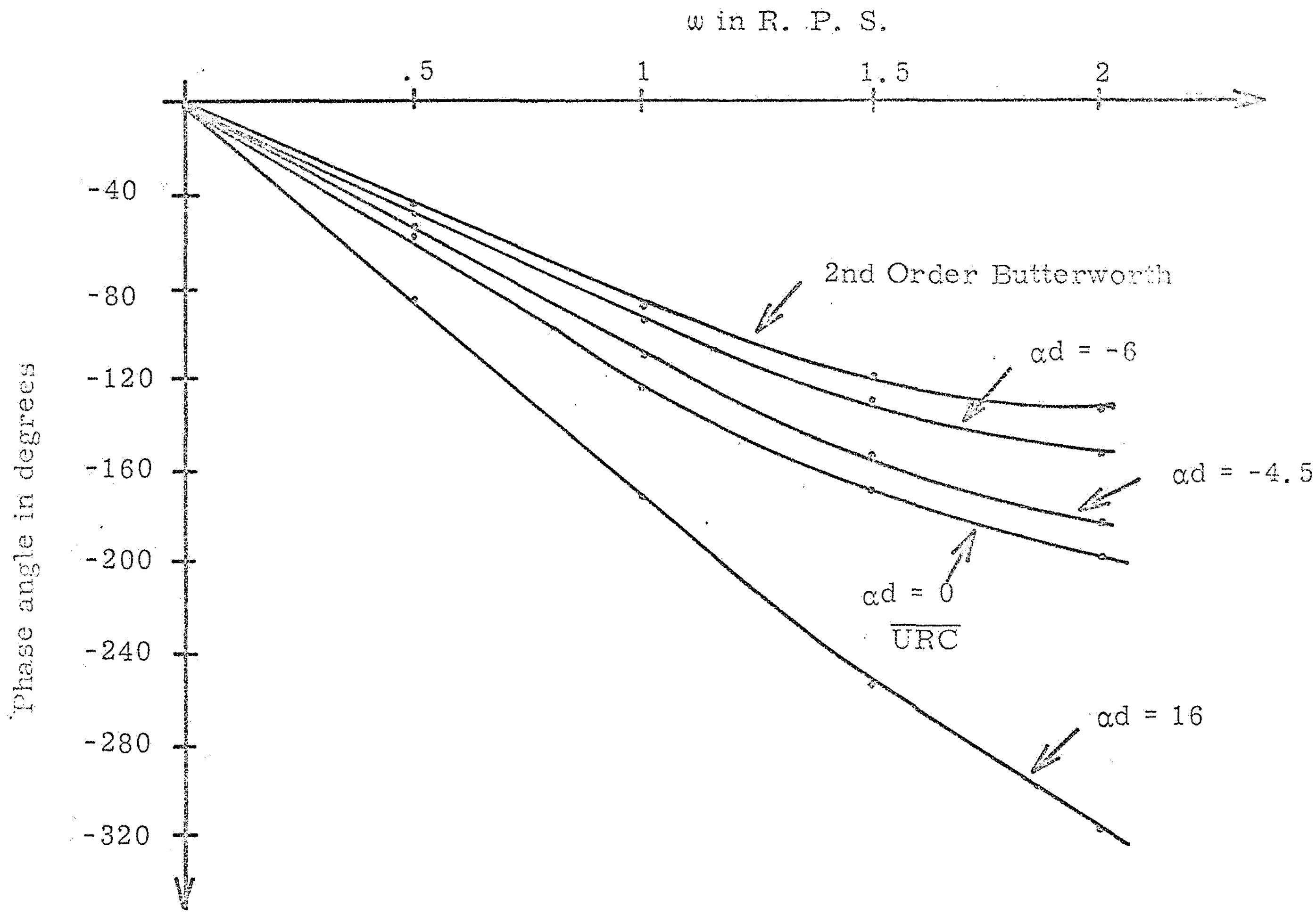

Figure 22. Phase Response for Various αd

Table 1. Magnitude and Phase Response of $\overline{URC}$ AN and 2 Complex-Conjugate Poles

ω	$\overline{URC}$ AN RESPONSE K=.70 and T=15		$\frac{\alpha^2+\beta^2}{(s+\alpha)^2+\beta^2}$ RESPONSE α=-0.489 and β=.589	
0	1.000	0	1.000	0
.100	1.003	-12.956	1.003	-9.630
.200	1.010	-26.292	1.010	-19.696
.300	1.016	-40.354	1.017	-30.584
.400	1.015	-55.381	1.013	-42.532
.500	.996	-71.389	.988	-55.471
.600	.951	-88.039	.932	-68.897
.700	.877	-104.657	.848	-81.978
.800	.783	-120.476	.748	-93.912
.900	.683	-134.948	.646	-104.246
1.000	.587	-147.877	.552	-112.917
1.100	.502	-159.332	.472	-120.093
1.200	.429	-169.508	.404	-126.024
1.300	.369	-178.629	.348	-130.953
1.400	.318	-186.898	.302	-135.087
1.500	.277	-194.482	.264	-138.588
1.600	.242	-201.513	.233	-141.586
1.700	.212	-208.096	.206	-144.176
1.800	.188	-214.311	.184	-146.436
1.900	.167	-220.221	.165	-148.423
2.000	.149	-225.876	.149	-150.184
2.100	.134	-231.313	.135	-151.755
2.200	.120	-236.565	.123	-153.165
2.300	.109	-241.655	.112	-154.438
2.400	.099	-246.605	.103	-155.594
2.500	.090	-251.431	.095	-156.647
2.600	.082	-256.146	.088	-157.611

REFERENCES

1. Margolf, J. M., "D-C Converter Circuit Uses Capacitors," Electronics, p. 97, March 29, 1966, Vol. 39, No. 6.

2. Patten, Ramme, and Roman, "Dry Electrodes for Physiological Monitoring," NASA TN D-3414, May, 1966, pp. 34.

3. Richardson, P. C, "The Insulated Electrode: A Pasteless Electrocardiographic Technique," Proceedings of the Annual Conference on Engineering in Medicine and Biology, 9:15.7, November, 1967.

4. Kerwin, W. J., "Synthesis of Active Networks Containing Distributed and Lumped Elements," OART Program Review, NASA-Ames Research Center, Moffett Field, California, August 23, 1967.

BIBLIOGRAPHY

APPENDIX A

1. N. M. Anderson, P. Sekelj, and M. McGregor, "The Transmission of red and infrared light through the human ear," IRE Trans. on Bio-Medical Electronics, vol. BME-8, pp. 134-135, April 1961.

2. N. M. Anderson and P. Sekelj, "Studies on the light transmission of nonhemolyzed whole blood, determination of oxygen saturation," J. Lab. Clin. Med., vol. 65, pp. 153-166, January 1965.

3. K. D. Broadfoot, "A Photoelectric apparatus for examining blood circulation in the interior of the eye," Electronic Engineering, vol. 34, No. 407, pp. 2-7, January 1962.

4. A. W. Melville, D. H. Smith, and J. B. Cornwall, "An improved recording oximeter," Electronic Engineering, vol. 32, No. 387, pp. 296-300, May 1960.

5. J. B. Cornwall, D. C. Marshall, and J. Boyes, "A cuvette oximeter and an extension to the theory of oximetry," J. Sci. Instruments, vol. 40, pp. 253-258, May 1963.

6. S. R. Gambino, "Laboratory suggestion: A simpler graph for use in determining oxygen saturation of blood by means of spectrophotometry," Amer. J. Clin, Path., vol. 43, pp. 599-600, June 1965.

7. S. R. Gambino, et al., "A micro method for determination of oxygen saturation by means of reflection spectrophotometry," Amer. J. Clin. Path., vol. 42, pp. 364-367, October 1964.

8. M. G. Heller, et al., "Continuous recording oximeters with clinical applications," Instrument Soc. of Amer, -J., vol. 1, No. 3, pp. 28-31, March 1954.

9. P. Hellung-Larsen, et al., "Photometric determination of oxyhemoglobin saturation in the presence of carbon monoxide hemoglobin especially at low oxygen tensions," Scand. J. Clin. Lab. Invest., vol. 18, pp. 443-449, 1966.

10. L. J. Henry, et al., "A graph for use in determining oxygen saturation of blood by means of spectrophotometry," Amer. J. Clin. Path., vol. 42, pp. 634-636, December 1964.

11. J. B. Hickam, "A study of retinal venous blood oxygen saturation in human subjects by photographic means," Circulation, vol. 27, pp. 375-385, March 1963.

12. D. W. Hill, "Methods of measuring oxygen content of blood," Int. Anesth. Clin., vol. 4, pp. 63-80, Spring 1966.

13. D. D. Van Slyke and J. M. Neill, "Determination of gases in blood and other solutions by vacuum extraction and manometric measurement," J. Biol. Chem., vol. 61, pp. 523-573, September 1924.

14. D. L. Drabkin and J. H. Austin, "Spectrophotometric Studies I. Spectrophotometric constants for common hemoglobin derivatives in human dog, and rabbit blood," J. Biol. Chem., vol. 98, pp. 719-733, November 1932,

15. D. L. Drabkin and J. H. Austin, "Spectrophotometric Studies V. A technique for the analysis of undiluted blood and concentrated hemoglobin solutions," J. Biol. Chem., vol. 112, pp. 105-115, December 1935.

16. R. Brinkman and A. J. H. Wildschut, "A clinical method for rapid and accurate determination of oxygen saturation in small amounts of blood," Acta Med. Scandinav., vol. 94, pp. 459-466, 1938.

17. K. W. Jacobi, "A method for continuous oxygen determination in the aqueous humor and vitreous humor of the living eye," Graefe. Arch. Ophthal., (German), vol. 168, pp. 61-69, February 5, 1965.

18. J. H. Johnstone, "Measurement of arterial and capillary blood oxygen tension," J. Clin. Path., vol. 19, pp. 357-363, July 1966.

19. Instrumentation Lab, Inc., "Fraction oxyhemoglobin and carboxyhemoglobin measurements with the I. L. Model 182 Co-Oximeter," Product Bulletin, Watertown, Mass.

20. D. L. Drabkin and R. B. Singer, "Sprectrophotometric Studies VI. A study of the absorption spectra of non-hemolyzed erythrocytes and of scattering of light by suspensions of particles, with a note upon the spectrophotometric determination of the pH within the erythrocyte," J. Biol. Chem. vol. 129, pp. 739-757, August 1939.

21. G. A. Millikan, "The Oximeter, an instrument for measuring continuously oxygen saturation of arterial blood in man," Rev. Sci. Instr., vol. 13, pp. 434-444, October 1942.

22. E. A. G. Goldie, "A device for the continuous indication of oxygen saturation of circulating blood in man," J. Sci. Instr., vol. 19, pp. 23-25, February 1942.

23. A. Hemingway and C. B. Taylor, "Laboratory tests of the oximeter with automatic compensation for vasomotor changes," J. Lab. Clin. Med., vol. 29, pp. 987-991, September 1944.

24. D. L. Drabkin and C. F. Schmidt, "Spectrophotometric Studies XII. Observation of the circulating blood in vivo, and the direct determination of the saturation of hemoglobin in arterial blood," J. Biol. Chem., vol. 157, pp. 69-83, January 1945.

25. A. Roos, J. O. Elam, J. F. Neville, Jr., and H. L. White, "Oximetric determination of cardiac output in man," Fed. Proc. (Abstract), vol. 7, p. 104, March 1948.

26. N. S. Kapany, et al., "Fibre optics spectrophotometer for in vivo oximetry," Nature, (London), vol. 204, pp. 138-142, 10 October 1964.

27. E. H. Wood, J. E. Geraci, and D. L. Groom, "Photoelectric determination of blood oxygen saturation in man," Fed. Proc., (Abstract), vol. 7, p. 137, March 1948.

28. F. W. Hartmen, V. G. Behrmann, and F. W. Chapman, "A photoelectric oxyhemograph, a continuous method for measuring the oxygen saturation of the blood," Amer. J. Clin. Path., vol. 18, pp. 1-13, January 1948.

29. J. Knutson, B. E. Taylor, and E. H. Wood, "Oximetric method for determination of the oxygen saturation of mixed venous blood in man," Fed. Proc., (Abstract), vol. 8, p. 87, March 1949.

30. J. H. Comroe, Jr., and E. H. Wood, "Measurements of O_2 saturation of blood by filter photometers (oximeters)," in Methods in Medical Research, Comroe, Jr. and H. Julius, Eds., Chicago, Illinois: Year Book (c1950), section 2, pp. 144-159.

31. J. O. Elam, J. F. Neville, Jr., W. Sleator, and W. N. Elam, Jr., "Sources of error in oximetry," Ann. Surg., vol. 130, pp. 755-773, October 1949.

32. D. W. Lubbers, "Methods of measuring oxygen tensions of blood and organ surfaces," Int. Anesth. Clin., vol. 4, pp. 103-127, Spring 1966.

33. E. H. Wood and J. E. Geraci, "Photo-electric determination of arterial oxygen saturation in man," J. Lab. Clin. Med., vol. 34, pp. 387-401, March 1949.

34. E. H. Wood, B. E. Taylor, and J. Knutson, "Oximetric measurement of circulation time and arterial saturation time during oxygen breathing in man," Fed. Proc., (Abstract), vol. 8, p. 171, March 1949.

35. E. H. Wood, "Oximetry," in Medical Physics, vol. 2, O. Glasser, ed., Chicago, Ill. " 1950, pp. 664-680.

36. A. H. Maas, et al., Microspectrophotometric determination of the haemoglobin oxygen saturation in haemolyzed arterialized capillary blood.," Clin. Chem. Acta., vol. 9, pp. 236-240, March 1964.

37. F. X. Mack, "The value of the ear oximeter in medicine today," J. Maine Med. Assoc., vol. 53, pp. 116-119, May 1962.

38. F. W. Hartman, V. G. Gehrmann, and R. D. McClure, "The oxyhemograph," Amer. J. Surg., vol. 78, pp. 867-869, December 1949.

39. R. L. Longini and R. J. Zdrojkowski, "An optical theory for materials which both scatter and absorb," Proc. of the 20th Ann. Conf. on Eng'g. in Med. and Bio., vol. 9, p. 5.1, November 1967.

40. Y. Enson, W. A. Briscoe, M. L. Polanyi, and A. Cournand, "In vivo studies with an intravascular and intracardiac reflection oximeter," J. Appl. Physiol., vol. 17, pp. 552-558, May 1962.

41. J. D. Sinclair et al., "Apparent dye-dilution curves produced by injection of transparent solutions," J. Appl. Physiol., vol. 16, pp. 669-673, July 1961.

42. J. Amesz, L. N. M. Duysens, and D. C. Brandt, "Methods for measuring and correcting the absorption spectrum of scattering suspensions," J. Theor. Biol., vol. 1, pp. 59-74, January 1961.

43. P. Sekelj and M. McGregor, "Estimation of cardiac output in man using an ear oximeter and Coomassie blue dye," IRE Trans. on Bio-Medical Electronics, vol. BME-8, pp. 127-133, April 1961.

44. M. Makino et al., "Measurement of high concentrations of oxygen in the Scholander apparatus," Jap. J. Clin. Path., vol. 14, pp. 625-627, September 1966.

45. R. Margaria, "A mathematical treatment of the blood dissociation curve for oxygen," Clin. Chem., vol. 9, pp. 745-762, December 1963.

46. K. H. Norris, and W. L. Butler, "Techniques for obtaining absorption spectra on intact biological samples," IRE Trans. on Bio-Medical Electronics, pp. 153-157, July 1961.

47. J. P. Payne, and D. W. Hill, eds., "Oxygen measurements in blood and tissues and their significance," Proc. of Symposium on Oxygen Measurements in blood and tissues and their significance, London, 1964, (Boston; Little, Brown, 1966).

48. W. Paul, "Contribution to oximeter design using modulated light," Fed. Proc. (Abstract), vol. 9, p. 99. March 1950.

49. W. Paul, "An oximeter for continuous absolute estimation of oxygen saturation," J. Sci. Instr., vol. 30, No. 5, pp. 165-168, May 1953.

50. P. Sekelj, "Further Studies on oximetry," Am. Heart J., vol. 48, pp. 746-774, November 1954,

51. W. Paul, "Analogue computer for ac oximetry," (Note), J. Sci. Instr., vol. 32, p. 286, July 1955.

52. P. Sekelj and A. L. Johnson, "Photo-electric method for estimation of the oxygen saturation of non-hemolyzed whole blood," J. Lab. Clin. Med., vol. 49, pp. 465-477, March 1957.

53. R. H. Kay and R. V. Coxon, "Optical and instrumental limitations to the accuracy of oximetry," J. Sci. Instr., vol. 34, pp. 233-236, June 1957.

54. W. Paul, "Oximetry," IRE Trans. on Medical Electronics, vol. PGME-11, pp. 34-38, July 1958,

55. M. L. Polanyi, "In vivo oximeter with fast dynamic response," Rev. Sci. Instruments, vol. 33, No. 10, pp. 1050-1054, October 1962.

56. M. L. Polanyi and R. M. Hehir, "New reflection oximeter," Rev. Sci. Instr., vol. 31, pp. 401-403, April 1960.

57. M. Querci et al., "Hemocynamic changes in experimental CO poisoning," Rass. Med. Industr., (Italy), vol. 33, pp. 454-455, May-August 1964.

58. W. J. Reichert, "The theory and construction of oximeters," Int. Anesth. Clin., vol. 4, pp. 81-102, Spring 1966.

59. P. Sekelj, M. McGregor, and W. Adam, "An ear oximeter for the estimation of Coomassie blue dye in blood," Proc. third Internat'l Conf. on Med. Electronics, London, July 1960. London: Institution of Electrical Engineers, 1961, pt. 2, pp. 230-232.

60. G. Richter, "Quantitative studies on the change in reflex oxymetric values by optical intermediate layers," Acta. Biol. Med. German, (German), vol. 10 , pp. 284-291, 1963.

61. J. Richter et al., "On the effect of leukocytes as unstained particles on the results of reflection oximetry," Pflueger Arch. Ges. Physiol., (German), vol. 282, pp. 232-237, 1965.

62. F. A. Rodrigo, "The determination of the oxygenation of blood in vitro by using reflected light," Am. Heart J., vol. 45, pp. 809-822, June 1963.

63. R. H. Taplin, H. G. Saville, and W. Paul, "Improved earpieces for oximeters," J. Aviation Med., vol. 24, pp. 70-72, February 1953.

64. F. D. Stott, "Portable oximeter with provision for continuous recording," J. Sci. Instruments, vol. 30, No. 4, pp. 120-123, April 1953.

65. G. R. Tait, P. Selelj, and G. L. D'Ombrain, "A theoretical analysis of some errors in oximetry," IEEE Trans. on Bio-Medical Eng'g., vol. BME-13, No. 4, pp. 200-206, October 1966.

66. E. H. Wood, W. F. Sutterer, and L. Cronin, "Oximetry," in Medical Physics, vol. 3, O. Glasser, Ed., Chicago, Ill.: Year Book, (c1960), pp. 416-445.

67. N. J. Nelsson, "Oximetry," Physiol. Rev., vol. 40, pp. 1-26, January 1960.

68. P. Sekelj, D. V. Bates, A. L. Johnson, and W. Jegier, "Estimation of cardiac output in man by dye dilution method using an automatic computing oximeter," Am. Heart J., vol. 55, pp. 810-823, June 1958.

69. P. Sekelj, W. Jegier, and A. L. Johnson, "Automatic electronic computer for the estimation of arterial concentration of Evan's blue dye," Am. Heart J., vol. 55, pp. 485-503, April 1958.

70. D. Keilin and E. F. Hartree, "Spectrophotometric study of suspensions of pigmented particles," Biochem. Biophys. Acta, vol. 27, pp. 173-184, January 1958.

71. P. F. Ware et al., "A new reflection oximeter," J. Thor. Cardiov. Surg., vol. 42, pp. 580-588, November 1961.

72. W. G. Zijlstra, A Manual of Reflection Oximetry and Some Other Applications of Reflection Photometry., No. 152, p. 20, Van Gorcum's Medical Library, Koninklijke Van Gorcum & Co., Assen, Netherlands, 1958.

73. W. G. Zijlstra, Clinical Oximetry., p. 52, Van Gorcum & Co., Ltd., Assen, Netherlands, 1951.

74. R. Berzon, "Reflection oximetry in clinical function tests," Z. Tuberk., (German), vol. 123, pp. 27-35, February 1965.

75. J. Dorsch et al., "A rapid test for the determination of carbon monoxide in the blood by means of the Atlas oxymeter," Med. Welt., (German), vol. 19, pp. 1068-1070, May 8, 1965.

76. W. Paul, B. C. Grapes, and R. H. Taplin, "Vascular patterns in ear as a source of error in oximetry," Fed. Proc., (Abstract), vol. 11. p. 119, March 1952.

77. P. Sekelj, A. L. Johnson, H. E. Hoff, and M. P. Schuerch, "Photo-electric method for the determination of arterial oxygen saturation in man," Am. Heart J., vol. 42, pp. 826-848, December 1951.

78. E. H. Wood, "A single scale absolute reading ear oximeter," Proc. of the Mayo. Clin., vol. 25, pp. 384-391, July 5, 1950.

79. R. Brinkman and W. G. Zylstra, "Determination and continuous registration of the percentage oxygen saturation in clinical conditions," Arch. Chir. Neerl., vol. 1, No. 3, pp. 177-183, 1949,

80. B. L. Horecker, J. Biol. Chem., vol. 148, p. 178, 1943.

81. K. Thurzu and H. Brechtelsbauer, Oxymetrie, Kurt Kramer, Ed., (G. Thieme Verlag, Stuttgart, Germany, 1960), p. 96.

82. P. Hariharan and M. S. Bhalla, "A wide-range recording logarithmic photometer circuit," J. Sci. Instr., vol. 33, pp. 69-71, February 1956.

83. D. Keilen and E. F. Hartree, "Effect of low temperature on the absorption spectra of heamoproteins; with observations on the absorption spectrum of oxygen," Nature, vol. 164, pp. 254-259, August, 1949.

84. B. H. Bloom, "Preliminary investigation of the techniques of blood oximetry," Northeastern University, Elect. Eng. Report, December 1967.

BIBLIOGRAPHY

APPENDIX B

1. Agadzhanyan, N. A. et. al. "A Method of Fastening Electrodes for Registering an Electrocardiogram During Manned Space Flights," Problems of Space Biology, Vol. 1, NASA TT-F174, November, 1963, pp. 497-506.
2. Bel'Kevich, V. I., E. Yu, Vende and I. A. Vil'-Vil'yams, "Nonpolarizing Electrodes for Detecting Slowly Varying Biopotentials in Internal Cavities," Fiziologicheskiy Zhurnal SSSR im. I. M. Sechenova, 49, 3, pp. 379-381, 1963, NASA TT-F199, April, 1964.
3. Biomedical Sciences Instrumentation. "Physiological Monitoring of Animals During Space-Flight," (New York: Plenum Press, 1963).
4. Boter, J., A. Den Hertog, and J. Kuiper, "Technical Note: Disturbance-Free Skin Electrodes for Persons During Exercise," Medical and Biological Engineering, 4:91-95, January, 1966.
5. British Heart Journal. "Electrode Jelly in Electrocardiography," 27:105-115, January 27, 1964.
6. Burns, Douglas C. and Phillip D. Collnick, "An Inexpensive Floating-Mesh Electrode for EKG Recording During Exercise," Journal of Applied Physiology, November, 1966, pp. 1889-1891.
7. Cooper, R. "IEEE International Convention Record Reference:'Electrodes'," American Journal of EEG Technology, 9:1-22, 1963.
8. Day, J. L. and M. W. Lippit Jr. "A Long-term Electrode System for Electrocardiography and Impedance Pneumography," Psychophysiology, 1:174-182, October, 1964.
9. Electrical Engineering, "Instrumentation for Research on Human Performance," 78:1079-1084, November, 1959.
10. Geddes, L. A. and L. E. Baker, "Chlorided Silver Electrodes," Medical Research Engineering, 6:33-34, 3rd Quarter, 1967.
11. Goulding, L. G. "Electrocardiography," Instrument Practice, 16:1229-1241, October, 1962. (58 references)
12. Lewes, T. "Polarizable as Against Non-polarizable Electrodes," Journal of Physiology, 49 L-Lii, 1914-1915.
13. Pardec, "Concerning the Electrodes Used in Electrocardiography," American Journal of Physiology, 44:80-83, 1917.

14. Patten, Ramme, and Roman, "Dry Electrodes for Physiological Monitoring," NASA TN-D-3413, May, 1966, pp. 497-506.

15. Roman, James A. "Flight Research Program III - High Impedance Electrode Techniques," Aerospace Medicine, 37:790-795, August, 1966.

16. Roth, J. G., et. al. "The Use of Carbon Electrodes for Chronic Cortical Recording," Electroencephalography and Clinical Neurophysiology, 21:611-615, December, 1966.

17. Spach, M. S. et. al. "Skin Electrode Impedance and its Effects on Recording Cardiac Potentials," Circulation, 34:649-656, October, 1966.

18. Stanley, Paul E. "Monitors that Save Lives Can Also Kill," The Modern Hospital, 108:119-121, March, 1967.

19. Urmer, A. H. "Advanced Techniques in Medical Electronics," Electronics Industries, 23:42, July, 1964.

20. Weinman, Joseph and Jonah Mahler, "An Analysis of Electrical Properties of Metal Electrodes," Medical Electronics and Biological Engineering, 23:299-309, July, 1964.

21. AMRL TDR-69-98/2 (AD-428616), "Performance Characteristics of Electrodes, Signal Modifiers, and Graphic Recording Components in Physiological Monitoring Systems," (1964).

22. NASA CR-67798, "Electrode for Measuring Biopotentials at the Human Skin," (1966). (N66-10608 01-17)

23. NASA CR-56205, "Development of an Electrode for Long-Term Application in Biological Recording," (1964). (N64-25767 17-16)

24. NASA CR-82007, "Electrode Properties and an Equivalent Circuit of Surface Electrodes for Electrocardiography," (1967). (N67-10608 01-17)

25. 62-678. "Electrodes for Recording Bioelectric Current Signals for Applications in Signal, Analytical and Physiological Investigation Equipment, Including EEG, ECG, Electromyography," (1962).

26. A65-21947. "Long-Term ECG and Impedance Pheumograph Electrode System Composed of Ag, AgCl and Non-Irritating Paste," 11:1519, (1965).

27. A66-39790. "High Impedance Electrode Technique for Large-Scale Flight Physiological Data Collection Emphasizing Skin Preparation," 22:3859, (1966).

28. American Astronautical Society, "New Concepts in Monitoring of Astronauts' Brain Functions," Advances in Astronautical Sciences, VII:221-225, 1962.

29. American Heart Association, "Report of Committee on Electrocardiography," Circulation, 35:583-602, March, 1967.

30. Segal, M. J., Savoie, V. M., Electrodes for Physiological Measurements, Northeastern Report No. 1, 15 Dec. 1967.

31. Ibid, Report No. 2, 29 June 1968.